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NOISE CHARACTERIZATION
OF THE LINEAR CCD

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INTRODUCTION

This report summarizes work done in evaluating the noise performance of the linear CCD. The noise determines the minimum amplitude signal the CCD is capable of capturing and therefore is one of the prime parameters in determining dynamic range. The noise after correlated double sampling and correction of some ground loops will be shown equivalent to 150 rms electrons at the floating diffusion sensor on the CCD.

The CCD noise sources can be classified into three components: system noise, output noise, and charge related noise. System noise and output noise is independent of charge transport in the CCD channel. Typically, these noise sources can be measured by biasing off the input diffusions of the chip, so as not to inject any charge. To alleviate charge generated by dark current, the CCD should be clocked backward. The charge-related noise has been difficult to record because of the large system/output noise. A complete breakdown of the contribution of each of these noise sources will be given in Section III.

Figures 1A, 1B, and 1C shows the total noise on the clamp pedestal, reset pedestal, and output pedestal respectively. Some of the high frequency burst noise is evident on the output pedestal. The source of this noise will be shown in Section II to be ground noise. The switching power supplies that were originally used with the exerciser were changed to series regulated supplies but there was no noticeable improvement in the noise performance. The series regulated supplies were left in operation for the remainder of the measurements.

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I. Analysis of Output Noise Sources

The noise sources, that I classify under output noise, are those related to the output structure of the chip. Figure 2 shows a diagram of the output structure. T2 the source follower contributes thermal noise plus $1/f$ noise. T1 resets the floating diffusion capacitance C_0 and is responsible for KTC noise.

Thermal and $1/f$ Noise

Figure 3 shows a test circuit utilized for measuring the noise spectrum of T2. The resulting spectrum is shown in Figure 4A for 2 test fets of comparable size and processing as T2. Figure 4A also shows a plot for a Signetics SD 210 DMOS transistor. The curves show an increase in noise at lower frequencies ($1/f$ noise). I believe the high frequency rolloff may be due more to RC rolloff in the circuit due to parasitic capacitance as opposed to an actual decrease in the content of high frequency noise. Ideally the noise should taper off into some sort of asymptote at high frequency representing thermal noise which is uniformly distributed with frequency. This number is typically $10 \text{ nV}/\sqrt{\text{Hz}}$ at 1 MHz, lower than I would expect. The $1/f$ component does not have a nice corner frequency which is indicative of surface channel fets. I believe there is a larger component of noise at 60 Hz but since the wave analyzer has a minimum bandwidth of 200 Hz it is difficult to measure very low frequencies. Figure 4B shows a scope picture of the noise bandwidth limited by only the 5 MHz switch on the scope. The noise for the transistor appears no greater than 150-200 uv peak to peak.

Once the output transistor was characterized, I decided to bias a CCD

using the test circuit of Figure 5. The CCD input was biased in cutoff and the reset gate was D.C. biased at different levels. The device was not clocked and therefore some of the thermally generated charge in the channel may have found its way to the floating diffusion in these measurements particularly when the reset gate was biased negative making the floating diffusion a high impedance. Figure 6A shows the noise spectrum for two different reset gate biases. The noise spectrum of Figure 6A is not substantially different than that of just the source follower T2 as shown in Figure 4A. However, the scope pictures of the noise shown in Figure 6B show an increase in noise over those of the single transistor shown in Figure 4B. The scope pictures do show that the noise is lower frequency than the wave analyzer is capable of measuring. In section II, much of this will be shown to be 60 Hz.

KTC Noise

In order to calculate the theoretical KTC component as well as to be able to translate from measured voltages to measured electrons, the floating diffusion capacitance C_0 in Figure 2 was measured. A Keithly 616 electrometer was placed in series with the sink lead of the CCD to measure the recharge current of the floating diffusion. The exerciser was put into low frequency only mode during this measurement and one to five inputs were D.C. biased to inject charge. The ambient current measured was on the order of 2 to 7×10^{-8} amps with about .1 to 1×10^{-8} amps change as charge was injected. The period of the output waveform was 10 μ sec for 5 channels and 50 μ sec for one channel. After making a number of measurements in order to reduce measurement errors, I concluded there was about .09 pico coulombs for 1 volt change

at the output. Therefore, C_0 is .09 pf. The RMS number of KTC electrons should be $400(.09)^{1/2} = 120$. In Section III, I will show how this compares to the total measured noise for the output structure.

II. System Noise

I have concluded that system noise, generally 60 Hz, is the largest component of noise and usually manifests itself as bounce on the charge packets as well as high frequency spikes. The addition of proper grounding and a correlated double sampler can help minimize the system noise.

Ground Noise

In attempting to utilize a CDS circuit, I discovered a large amount (1 to 2 mv) of noise on the output of the circuit with the input open circuited. The noise at the output of the CDS circuit (with power off) and the scope in line sync is shown labeled as ground loop in Figure 7. The noise has a period of 8 ms with groups of 1 μ sec spikes at the 8 msec interval. Although the spikes occur in 8 ms groups they do not sync on the scope precisely using line sync and perhaps are generated by something like brushes on a motor. I found the spikes were considerably reduced when the circuit was hooked up on a different bench in the same room. By placing a ground strap from the back left hand corner of the exerciser to the switch box on the bench, the spikes were reduced by about a factor of ten (labeled single ended in Figure 7). There doesn't seem to be any simple rule in eliminating ground noise since the exerciser and its associated pulse generators are distributed over an entire workbench and rack. In general, ground loops should be avoided

but the ground noise must be monitored from time to time as signal sources are added or removed from the system. For example, when I removed the input signal generator I found the noise increased by a factor of about three. In addition to the ground strap, I went to differential mode with a Tektronix 7A13 PREAMP. The positive input measured the CDS output while the negative input measured ground near the CDS output. This addition left very little ground noise visible on the scope on the 1 mv/div scale (about 100 uv) as labeled differential in Figure 7. Although differential operation showed clearly that the noise was on the ground system it was not practical to utilize it in making measurements. With the CDS circuit powered up, there is usually more than 10 mv (the entire screen of the scope) difference between charge packets unless all five channels are sampling the same amplitude. Therefore, a lot of offset is generally needed and this is input on the negative input of the 7A13.

CDS Circuit

A correlated double sampler circuit was added to reduce both KTC noise and low frequency noise sources. The KTC noise of 120 rms electrons, from Section I, is probably not as significant as the $1/f$ noise and 60 Hz noise which get reduced by the CDS circuit if it is run at a high enough frequency. When I first hooked up the CDS circuit, I was running the output structure at about 10 kHz and the noise out of the CDS actually seemed to be greater than the noise on the packets at the input to the CDS. Of course the CDS circuit does nothing to reduce ground noise as discussed previously which adds to the output of the CDS circuit.

Figure 8 shows a schematic of the CDS circuit. See reference one for a description of the circuit. Figure 9 shows the timing of the two sample pulses with respect to the CCD output waveform at the output of the white follower. The CCD output structure was run at 100 kHz for the CDS measurements. I would have liked to run at a higher speed but settling times in the output structure limit the top speed to about 100 kHz. The most critical time is the settling of the reset pedestal which must occur in one quarter of the clock period. Figure 10 shows a picture of the CCD output running at 500 kHz and not allowing enough settling time. Figure 11 shows a comparison of the CDS output as well as its input from the white follower. The important thing in both traces is not the ringing and glitches which are fixed from shot to shot but the amount of vertical displacement for a given horizontal time point. This picture was taken with all inputs to the CCD biased off and therefore is a measure of system noise, and output noise. The noise has been improved by a factor of two to three by utilizing the CDS circuit.

III. Comparison of Noise Sources

I decided to make rms measurements of the noise in order to better quantize the various noise sources as well as to be able to compare our measured data to theoretical numbers. To obtain accurate rms measurements, I digitized the CDS outputs and fed them to our LSI-11 computer. My objective was to obtain a pulse height distribution on a given charge packet over a number of shots. From this probability distribution, I was able to calculate the rms value as $\sqrt{\sum (x - \bar{x})^2 p(x)}$ where x is the amplitude of the pulse, $p(x)$ is the probability of the pulse being at amplitude x , and $\bar{x}$ is the mean of the distribution.

Another method for measuring rms noise would have been to take the pulse height distribution of all the charge packets in the record on just one or two shots. I decided against this method since all the pulses in the record are not identical to each other even in the absence of noise. This is primarily due to the dark current ramp which causes pulses at the end of the record to be greater than those at the beginning.

Prior to A/D conversion the CDS output was amplified and sampled one more time to make the input compatible with the A/D converter. The A/D, a Lecroy 8210, is a 10 bit A/D with a ± 5 volt full scale input. This yields a sensitivity of about 10 mv/count. There is usually $\pm$ one count of noise on the A/D itself, so signals should be greater than 20 mv p-p to be measured at all. I worked with two gains, 20 (yielding 500 uv/count) and 80 (yielding 125 uv/count). I discovered with a gain of 20 that the noise on the CDS output (Figure 11) produced only a couple counts of variation on the A/D not enough to obtain good statistics particularly since it was about equal to the A/D noise. However 20 is about the maximum gain to prevent saturation of the A/D with the full well CCD output. Therefore, most the A/D noise measurements were made with the gain set at 80 to obtain a larger number of counts even though this gain was too large for full well measurements. The offset which was injected into the minus side of the amplifier was very touchy when running a gain of 80. In addition, it seemed to have some long term drift which could skew the pulse height distribution if run for too long a time. The number of shots was limited to 100 to prevent the offset from influencing the distributions too much.

To isolate one noise source from the other, I started by unplugging the CDS circuit input from the white follower output. The measured rms noise from the pulse height distribution was 162 uv. Knowing the rms noise of the CDS circuit, which includes system noise, I plugged the CDS input back into the white follower and with no charge flowing through the CCD measured the rms noise to be 182 uv. The difference between these measurements is the output noise. Therefore,

$$\sqrt{N_{\text{CDS}}^2 + N_{\text{output}}^2} = 182 \text{ uv}$$

or

$$N_{\text{output}} = 82 \text{ uv}$$

Finally, I injected about a half full well of charge into the input of the CCD with a D. C. bias. The rms noise increased to 262 uv. Therefore,

$$\sqrt{N_{\text{Charge Related}}^2 + N_{\text{CDS}}^2 + N_{\text{Output}}^2} = 262 \text{ uv}$$

$$\sqrt{N_{\text{Charge Related}}^2 + 182^2 \text{ uv}} = 262 \text{ uv}$$

$$N_{\text{Charge Related}} = 188 \text{ uv}$$

In summary the noise contributions are:

$$N_{\text{CDS}} = 162 \text{ uv rms}$$

$$N_{\text{Output}} = 82 \text{ uv rms}$$

$$N_{\text{Charge Related}} = \text{uv rms}$$

To compare these numbers with theoretical numbers it is necessary to convert them to rms numbers of electrons by dividing by q/C_0 where q is the electronic charge and C_0 is the floating diffusion capacitance calculated in Section I. This constant is 1.7 uv/electron which yields the equivalent rms electrons for each component as:

$N_{CDS} = 95$ electrons

$N_{output} = 48$ electrons

$N_{Charge\ related} = 110$ electrons

Theoretical Noise

The equations in this section can be found in reference 1. I have classified noise sources which are not explained by the equations of reference 1 as N_{other} . N_{other} is a catchall number and includes system noise since there isn't a theoretical calculation of the system noise.

CDS Noise

The correlated double sampler has two noise sources associated with it. The clamping of the clamp capacitor C_C and the sampling of C_S shown in Figure 8 produce KTC noise. The equivalent number of electrons for the clamping operation is given by:

$$n_D = \frac{400e^-}{A_2} C_O(pf) C_C(pf)^{-1/2}$$

A_2 is the gain of T_2 which is approximately unity

$$C_C = 200pf$$

The formula for the sampling operation is similar.

$$n_e = \frac{400e^-}{A_2 A_4} C_O(pf) C_S(pf)^{-1/2}$$

A_2 is the same as above

A_4 is the gain of the source follower the CDS circuit
and is also about unity

$$C_S = 200pf$$

Since the value of these two noise sources is so small, I must conclude that most the CDS circuit noise is N_{other} .

$$\sqrt{n_e^2 + n_D^2 + n_{\text{other}}^2} = 95$$

$$n_{\text{other}} \approx 95 \text{ electrons}$$

Output Noise

The thermal noise contribution of output transistor T2 has been assumed to be $10 \text{ nV}/\sqrt{\text{Hz}}$, since, I believe, Figure 4A has an artificial rolloff. This rolloff is caused by the RC time constant of the source follower driving the external capacitance of the outside world. By looking at the white follower output, this time constant appears to be 500 ns. The thermal noise contribution can then be calculated as:

$$n_{T2} = \frac{C_0}{q} V_{T2} \tau^{1/2}$$

where C_0 is the floating diffusion capacitance

q is the electronic charge

V_{T2} is the thermal noise in $\text{V}/\sqrt{\text{Hz}}$

τ is the rolloff time constant

therefore

$$n_{T2} = \frac{0.09 \times 10^{-12}}{1.6 \times 10^{-19}} (10 \text{ nV}/\sqrt{\text{Hz}}) \left(\frac{1}{2(500 \text{ ns})} \right)^{1/2}$$

$$= 5.6 \text{ electrons}$$

The KTC noise, n_1 , previously calculated in Section I of 120 electrons gets reduced by the CDS circuit. The amount of reduction is given by

$$n_A = n_1 \left(2 \left(1 - e^{-\frac{(t_4 - t_2)}{\text{Roff } C_0}} \right) \right)^{1/2}$$

t_2 is the time the clamp pulse occurs

t_4 is the time the sample pulse occurs

R_{off} is the leakage resistance of the floating diffusion and is about 10^8 ohms

C_o is the floating diffusion capacitance.

The time difference between sample pulses is about 1 μ sec.

$$\begin{aligned} n_A &= 120 [2(1 - e^{-1 \times 10^{-6}/(1 \times 10^8 \times .09 \times 10^{-12})})]^{1/2} \\ &= 120 [.21]^{1/2} = 55 \text{ electrons} \end{aligned}$$

The combined effect of the thermal and KTC noise is

$$N_{\text{output}} = \sqrt{55^2 + 5.6^2} \cong 55 \text{ electrons}$$

This number compare fairly close with the measured value for N_{output} of 48 electrons.

Charge Related Noise

The charge related noise sources are those introduced at the input structure, those generated in association with dark current, and those produced by bulk trap emission. The charge introduced at the input structure is given by:

$$n_{in} = \frac{1}{q} (\alpha k T C_{in})^{1/2}$$

where C_{in} is the capacitance of the input well. This capacitance is about .02 pf. A is about unity.

$$\begin{aligned} n_{in} &= \frac{1}{1.6 \times 10^{-19}} [(4.1 \times 10^{-21})(.02 \times 10^{-12})]^{1/2} \\ n_{in} &= 56 \text{ electrons} \end{aligned}$$

This number is subject to some debate since the above formula is for fill

and spill operation. The input structure was run in diode injection mode for the measured data which could increase this number. I have not as yet made any measurements of the charge related noise with the input structure in the equilibration mode.

The shot noise associated with the dark current is given by:

$$N_{JD} = \frac{J_D A_S M}{q f_c}^{1/2}$$

J_D is the dark current density = 20 na/cm^2

A_S is the channel area under 4 electrodes = $3 \times 10^{-6} \text{ cm}^2$

f_c is the clock frequency of the input register = 20 kHz

M is the number of stages = 132

$$N_{JD} = 50 \text{ electrons}$$

At the present time I do not have a theoretical number for the bulk trap noise nor do I have a number for any system noise present at the input of the CCD. N_{other} will include both these noise sources:

$$\sqrt{N_{JD}^2 + N_{\text{in}}^2 + N_{\text{other}}^2} = N_{\text{measured}}$$

$$\sqrt{50^2 + 56^2 + N_{\text{other}}^2} = 110$$

$$N_{\text{other}} = 80 \text{ electrons}$$

SUMMARY

The total rms noise utilizing a correlated double sampler (CDS) circuit was measured to be 150 electrons. The noise is composed of three components the CDS circuit noise with 95 electrons, the CCD output structure with 48 electrons, and the CCD charge related noise with 110 electrons. The output structure noise can be almost completely accounted for as KTC noise not

removed by the CDS circuit. The charge related noise can be partially accounted for in terms of shot noise associated with dark current generation and input structure noise. The noise on the CDS circuit itself, I believe, is due to ground noise since it appears on the scope at a 120 Hz rate.

REFERENCES

1. R. W. Broderson and S. P. Emmons, "The Measurement of Noise in Buried Channel Charge Coupled Devices," 1975 International Conference on the Application of Charge Coupled Devices, pp. 331-349, October 1975.

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Figure 1B. Noise on the CCD output just following the reset clamp (reset pedestal).

Figure 1C. Noise on the CCD output during signal time (signal pedestal).

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Figure 3. Test circuit for evaluating 1/f noise performance of the output fet.

Figure 4A. 1/f noise performance for two different output fets and a commercial device.

Figure 4B. Oscilloscope picture of noise from the fet band width limited at 5 MHz.

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