EXPERIMENTAL CHARACTERIZATION OF CHARGE TRANSFER EFFICIENCY IN SURFACE CHANNEL CHARGE-COUPLED DEVICES

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ABSTRACT. The single most important characteristic of a charge-coupled device is its charge transfer efficiency (CTE). There are three basic types of loss which degrade CTE: fixed loss, proportional loss, and nonlinear loss. Examples will be given of each type of loss and new techniques for measurement of all three types of loss are described. A method of determining the minimum fat zero (fz) which eliminates fixed loss is shown and an experiment is presented which confirms that fixed loss due to surface states can be completely eliminated by the use of an fz. The effect of interelectrode gaps on CTE is discussed in detail. A nonlinear loss model is used to describe the dispersion due to barriers in the gaps and the very detrimental effect of wells in the gap region is shown. The techniques presented in the analysis of these losses are very general and can be used whenever a detailed description of the transfer loss mechanism is required.

I. INTRODUCTION

As the sophistication of charge-coupled devices (CCDs) increases, so should the technique used to evaluate and characterize these devices. There has, however, been little progress in new methods of measuring and modeling the dispersion since Berglund[1] defined the inefficiency factor as

$$\epsilon = \frac{\Delta N}{N_{sig} - N_{fz}}$$

where ΔN is the net charge trapped from a large charge packet; N_{sig} is the signal charge; and N_{fz} is the continuously introduced background charge of fat zero (fz). In this paper some new methods of measuring the transfer inefficiency will be described. These techniques will be used to show that fixed loss from surface states can be entirely eliminated from surface channel devices by use of a fat zero and a method will be given to determine the minimum level of the fz required to eliminate this loss. Also, a generalization of the inefficiency parameter, $\epsilon(N)$, will be defined which is a function of the signal amplitude and a technique which can be used to evaluate $\epsilon(N)$ will be presented. An application of this technique will be made to a device which is operating with a dispersion which cannot be described by the usual ϵ and the usefulness of the generalized form, $\epsilon(N)$, is thereby demonstrated.

In order to show the application of these new techniques, two aspects of the charge transfer mechanism will be discussed: (1) the effect of surface states and (2) the effect of the exposed interelectrode gap. For simplicity, an N-channel device was always used for measurements and analysis. A few general definitions and descriptions will now be given.

II. GENERAL CHARGE TRANSFER LOSS CONSIDERATIONS

To characterize the charge transfer loss in a CCD, it is useful to distinguish between three types of loss.

1. *Fixed loss*, which usually results from surface state trapping but can also arise from "wells" in regions of uncontrolled surface potential. This contribution is designated "fixed" because the loss is independent of signal amplitude. It can be eliminated by a proper background charge or fz.
2. *Proportional loss* has many possible causes such as "edge effect" or transit time losses, when these losses are small. This loss is proportional to signal amplitude, and although it generally decreases with increasing fz level, it cannot be eliminated. This type of loss can be characterized by an inefficiency parameter, ϵ, which is independent of signal amplitude.

3. *Nonlinear loss* is a more general phenomenological description of transfer loss which includes the dependence of the loss on signal amplitude, which can be nonlinear. Although this general model actually includes losses 1 and 2 as special cases, they will be specifically excluded in this definition. Potential "barriers" in the interelectrode gap region are an example of a loss which must make use of this more general description of the transfer inefficiency. The inefficiency parameter $\epsilon(N)$ is generalized by allowing it to have a dependence on the signal amplitude N. With this generalization, it is usually not possible to obtain simple expressions for the dispersion of a pulse train as it transfers along the device, and computer simulation of CCD operation must be used.

The usual method of measuring the inefficiency parameter ϵ is presented in Figure 1, which shows a long train of uniform signal charges (five shown here) in the midst of a long series of fz's. Δ_T is the difference between the signal charge and the fz charge. The differences Δ_1, Δ_2, etc., are the amounts of charge missing from the first, second, etc., pulses in the train; and Δ_1', Δ_2', etc., are the amounts of charge in excess of fz charge which emerge in the first, second, etc., pulses trailing the pulse train. The normalized total loss in the leading edge (L_L) is defined as

$$L_L = \frac{1}{\Delta_T} \sum_i \Delta_i \qquad (2)$$

and the normalized total loss in the trailing edge (L_T) is defined by

$$L_T = \frac{1}{\Delta_T} \sum_i \Delta_i' \qquad (3)$$

Proportional loss gives rise to a pulse train, symmetric in appearance, in which $\Delta_1 = \Delta_1'$, $\Delta_2 = \Delta_2'$, etc. Furthermore, Δ_i can be calculated as a function of the loss per transfer parameter ϵ by the relation

$$\Delta_i = \sum_{k=1}^{n} (-1)^{k+1} \epsilon^{k+i-1} \binom{n+i-1}{k+i-1} \binom{k+i-2}{i-1} \qquad (4)$$

where n is the number of transfers in the device and $\binom{i}{j}$ is the binomial coefficient. Using Equation (2), it can be shown that

$$L_L = L_T = n\epsilon \qquad (5)$$

which is independent of signal amplitude.

Fixed loss, on the other hand, gives rise to a nonsymmetric-looking pulse train. The effect of a fixed loss on the leading edge of a pulse train is to increase Δ_1 (see Figure 1). If the loss is large enough so that Δ_1 is equal to Δ_T, then Δ_2 increases and so on. On the other hand, the emission of the charge after the trailing edge of the pulse train is usually relatively slow and it takes many pulses for the charge to be reemitted. Of course, $L_L = L_T$ (unless

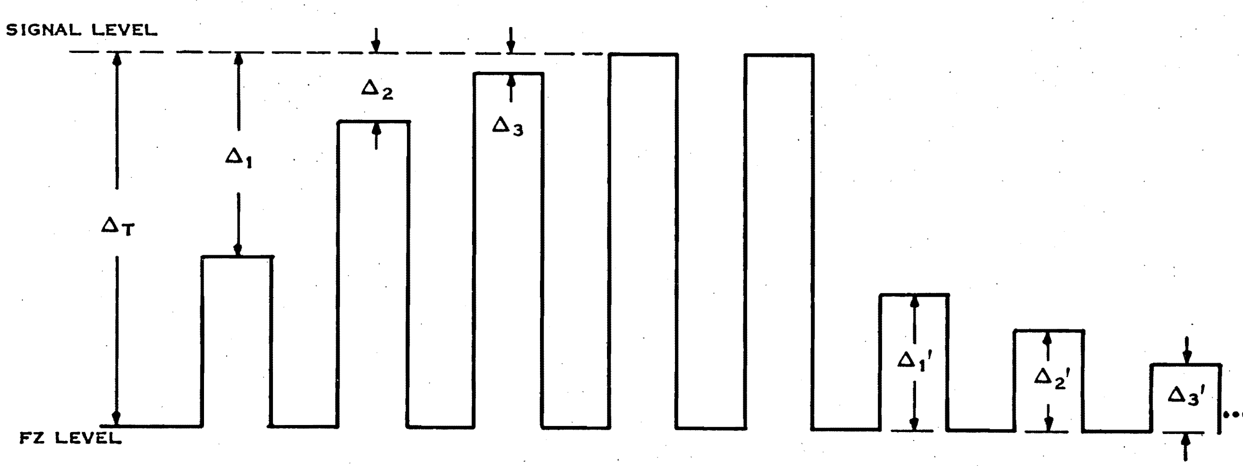

Figure 1. Schematic of a Pulse Train Showing Five Pulses

charge is being lost to the substrate), but in general $\Delta_i \neq \Delta_i'$.

Nonlinear loss, however, is even more complicated. For example little information can be gained about the loss from barriers by use of the above method. A new technique will be presented which makes possible an evaluation of the parameters involved in modeling a nonlinear loss.

III. SURFACE STATE LOSS

A. MEASUREMENT OF FIXED LOSS

The transfer inefficiency caused by surface states is a fixed loss and can be eliminated by continually transferring a small bias charge (fat zero) into the device in addition to the desired input signal. Surface state loss results when the surface state quasi-Fermi level which is set by the fz is too low (fz too small).

If the surface states are filled all the way to the conduction band by a large signal, then upon transfer of the signal to the next well, all the states will empty which have an emission time τ longer than the transfer time T of the signal charge packet. Since the emission time τ of a surface state is related to the energy of that state, E, by $\tau \sim e^{E/kt}$, an energy $E(\tau)$ can be defined which corresponds to the energy level of surface states with an emission time τ. The surface states will therefore empty to energy E(T) after transfer. The charge that is emitted from the surface states with energies greater than E(T) (emission times shorter than the transfer time) will transfer along with the main charge packet and will therefore not result in any loss. However, the charge in the surface states at energies $E < E(T)$ (emission times longer than the transfer time) will be collected in the trailing wells and thus contribute to transfer inefficiency. When the CCD is operated with an fz, then the surface states are filled by the fz to the level E_{fz}. Then, if $E_{fz} > E(T)$, there will be no fixed loss. However, if $E_{fz} < E(T)$, then when a signal charge which fills the surface states passes through a given well, it will leave behind $N_{ss}[E(T) - E_{fz}]$ electrons. The surface state density, N_{ss}, is assumed to be constant across the energy gap. The net charge captured from the signal charge packet after n transfers is then approximately given by

$$\text{Fixed Loss} = n\, N_{ss}[E(T) - E_{fz}] \qquad (6)$$

A more complete analysis of the surface state loss can be found in Reference 2.

In determining the amount of fz required to eliminate this fixed loss, one can simply increase the fz until the loss in the first pulse is equal to the charge in the first trailing pulse. At this point the loss is proportional and the fixed loss due to surface states has been eliminated. (Note that even with a large fz, surface states will still contribute to loss via the "edge effect," but this contribution will be proportional to the signal amplitude and not a fixed loss.)

A more accurate determination of fat zero required may be obtained by measuring the sum of the losses in the leading edges ($\sum_i \Delta_i$) versus input signal level (Δ_T). In Figure 2 this unnormalized total loss is measured on a 64-bit device as a function of signal level for a fz level of 0.11, 1.1 and 20 percent. The proportional loss (slope of the lines) is nearly independent of fz level (actually, it decreases slightly with increasing fz), but the dramatic part of the measurement is the shift along the vertical axis. The 0.11-percent fz curve extrapolates to a fractional fixed loss of 0.34 of a full well, which for 193 transfers gives 1.8×10^{-3} per transfer. The 1.1-percent fz curve extrapolates to a fixed loss of 1.0×10^{-3} per transfer, whereas the 20-percent fz curve extrapolates to zero fixed loss. (On this particular device, the fixed loss disappears at about 10 percent fz, and the curves shift very little with further increases in the fz level.)

In this measurement the determination of the fz level was made by monitoring the average current at the output of the device using a picoammeter. Measurement of the current can be used to obtain a very accurate determination of a full well and fz levels and makes it possible to calibrate the signal from the output circuitry in terms of charge.

B. VERIFICATION THAT FIXED LOSS IS ELIMINATED BY FAT ZERO

The results of the previous section indicate that if a sufficiently large fz is used, fixed loss can be eliminated and thus very small signal levels can be transferred with acceptable loss. This result is very important in the operation of surface channel CCDs in applications involving low signal levels, such as low light level imaging. Because of this importance, an experimental verification of this result was undertaken. In order to eliminate problems with noise in the measurement, the loss was determined by measuring the modulation transfer function (MTF) with the experimental apparatus shown in Figure 3. A sinusoidal input of frequency f was capacitively coupled through

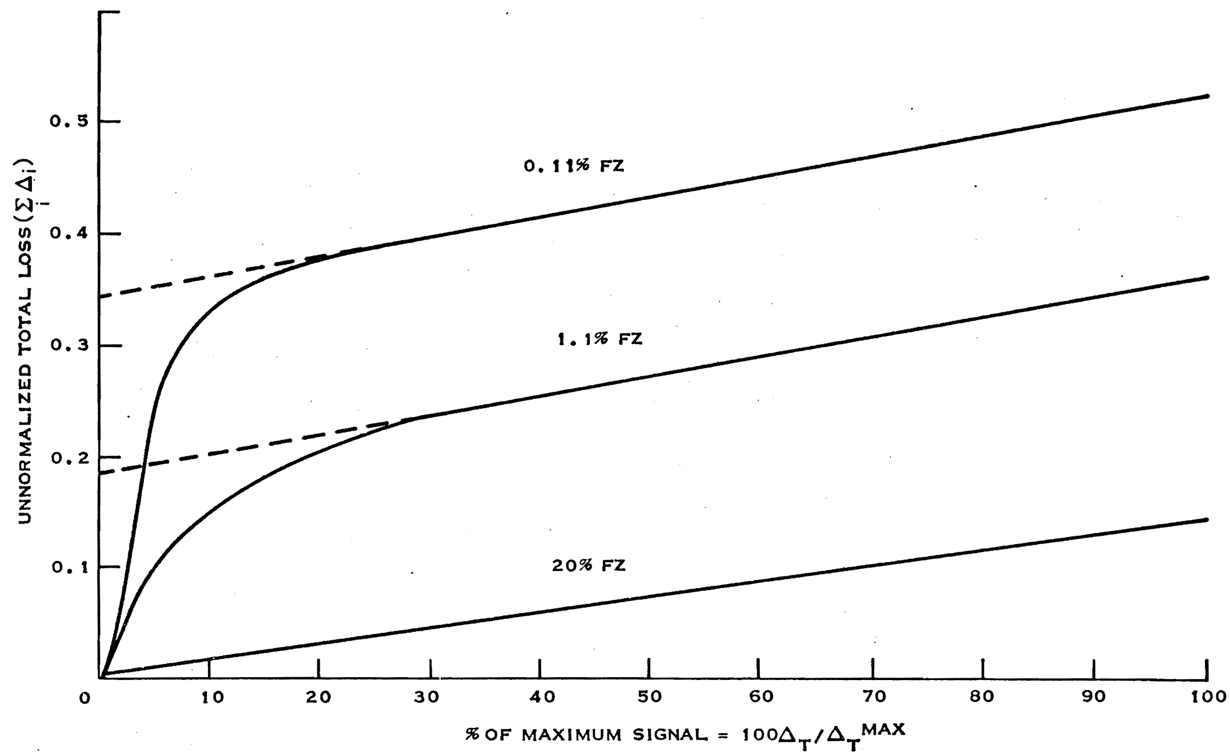

Figure 2. Unnormalized Total Loss versus Signal Level (Loss consists of a fixed loss and a proportional loss; the fixed loss can be eliminated by a sufficiently large fz.)

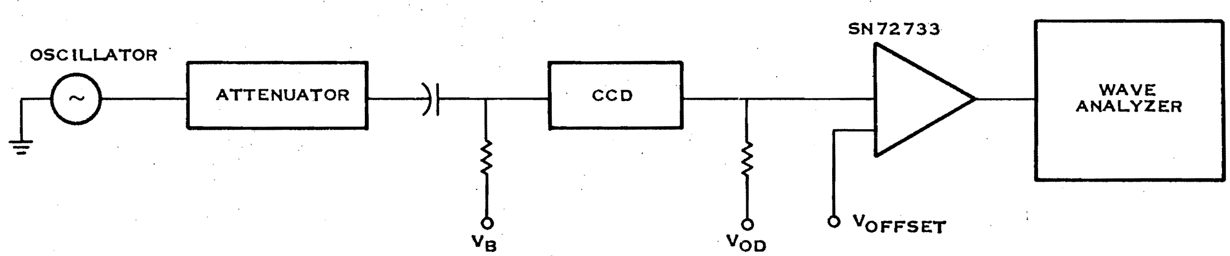

Figure 3. Circuit for Measuring Frequency Response (MTF) of a CCD as a Function of Signal Level

an attenuator to the input of a CCD. The fz level as determined by V_B was set at approximately half a full well so that a maximum ac signal could be achieved. The CCD output was amplified using a wideband video amplifier (SN72733) and fed to the wave analyzer. The MTF was measured at the maximum signal level, and then the signal was attenuated in 10-dB increments down to -60 dB. The limitation at -60 dB was due to the noise in the external circuitry (primarily the video amplifier); if care were taken to eliminate these external noise sources, much lower signal levels could be attained.

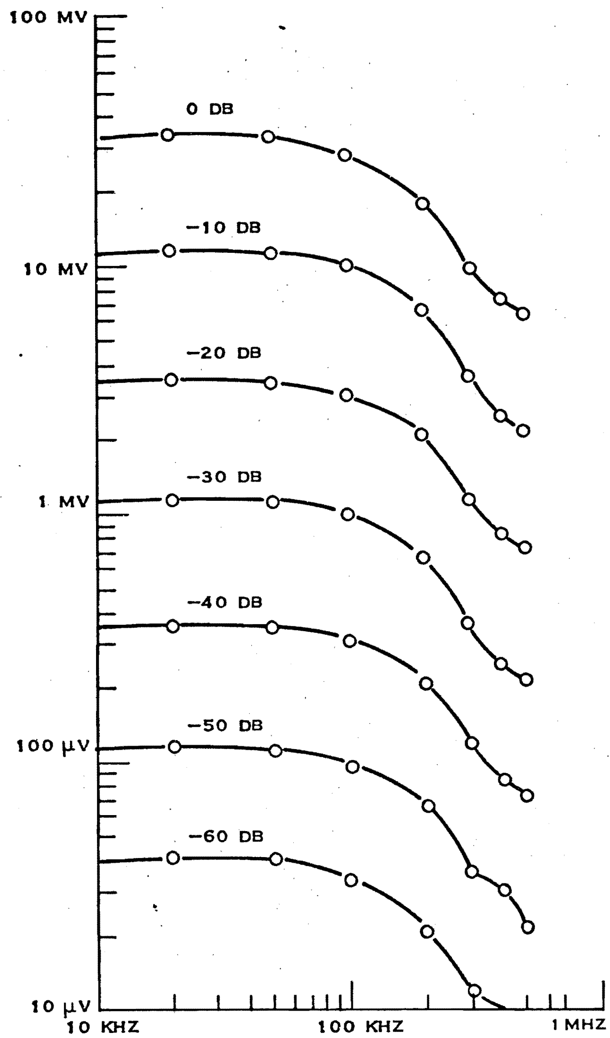

Figure 4. Measured Frequency Response (MTF) for Signal Levels Spanning 60 dB

Measurements of the MTF (frequency response) were made and compared with the expression for MTF

$$\mathrm{MTF(f)} = \exp\left[-n\epsilon\left(1 - \cos\frac{2\pi f}{f_c}\right)\right] \qquad (7)$$

where N is the number of transfers and f_c is the clock frequency. The experimental results are shown in Figure 4 for a device having 300 transfers at a clock frequency of 1 MHz. When ϵ is chosen to be 2.7×10^{-3}, the curves calculated using Equation (7) agree with the experimental curves to within the experimental error. The transfer loss for this device is far from optimum, but one thing is strikingly clear: the loss is independent of signal amplitude over at least a 60-dB range of signal level. By extrapolation, we believe this is true over an even wider range.

This measurement therefore proves that even though a high density of fast surface states is detrimental from a noise standpoint, their effect on transfer efficiency can be largely eliminated provided a sufficiently large fz is used (which is usually 10 to 15 percent).

IV. EFFECT OF THE INTERELECTRODE GAPS

A. CHARGE IN THE GAP REGION

The interelectrode gaps in CCDs which are fabricated photolithographically with a single level of metallization are limited to 2 to 3 μm. If these gaps are not covered by means of a "resistive sea," it is possible for potential barriers and wells to develop in this region. In the gap, the only capacitance is the small depletion layer capacitance so that a very small amount of charge in this region results in a large surface potential. In an exposed gap, the surface potential for an n-channel device tends toward the free surface potential, Φ_{fs}, which is given by

$$\Phi_{fs} = \frac{Q^2_{TOTAL}}{2q\epsilon_{si}N_A} \qquad (8)$$

where Q_{TOTAL} is the total amount of charge per unit area in the gap region. This total charge is composed of the fixed positive charge which exists at the oxide-silicon interface as well as all of the impurity charge which exists in and above the gate oxide. (See upper half of Figure 5.) For a sufficiently wide gap, the surface potential would attain this value, but for gaps of interest ($\approx 3\mu$), the surface potential in the gap region is determined mainly by the fringing fields. For this case it is necessary to numerically solve the two-dimensional Poisson equation to determine the size of the barriers or wells.

The effect of the interelectrode potential on transfer efficiency is shown in Figure 6. The device used in this figure was a 3-phase, n-channel, 100-bit serial shift register with 0.4- by 1-mil electrodes with 0.1-mil gaps. The device was clocked at 1 MHz with drivers which operated between 0 and 15 volts, and 15 percent fat zero. The substrate was biased with a negative voltage which was then varied and measurements of loss were made. This variation of loss with substrate voltage can be understood by referring to Figure 5. For this

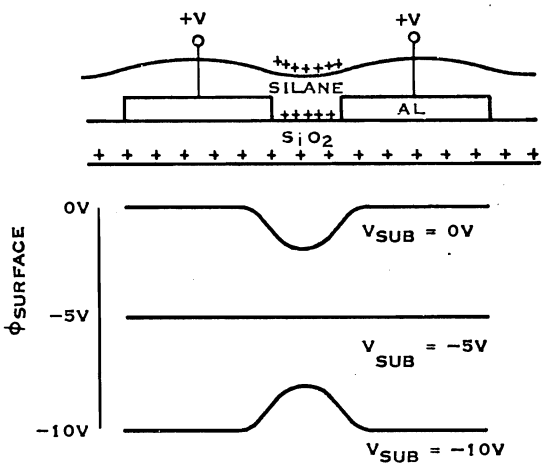

Figure 5. The Formation of Barriers and Wells by Varying the Substrate Bias

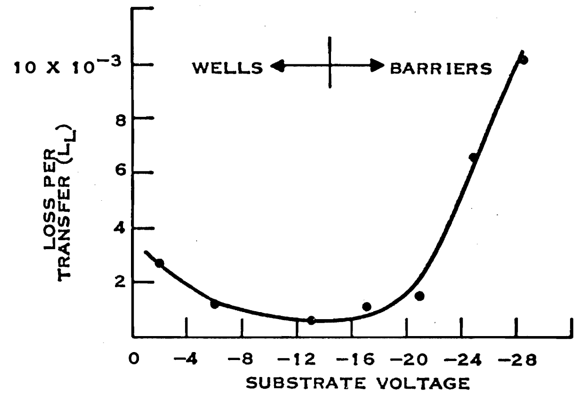

Figure 6. Loss per Transfer as a Function of Substrate Voltage

figure, the free surface potential as calculated by Equation (8) is +5 volts. For this value of Φ_{fs} and a gate to substrate voltage, V_{g-s}, on both gates of +5 volts, there will be no barriers or wells in the gap between these gates. However, if V_{g-s} is decreased to zero volts a well will appear in the gap. On the other hand, if V_{g-s} is increased to 10 volts, a barrier will arise. The actual mechanism of the loss resulting from the barriers and wells requires a more complicated model than that shown in Figure 6, but the essential point to be obtained from this figure is that there is an optimum gate to substrate voltage for a given charge in the gap region which minimizes the effect of the barriers and wells. Unfortunately, since the charge above the gate oxide is extremely dependent on environmental conditions, the optimum voltage for operation is also variable and thus CCDs with exposed oxide have unstable operating characteristics. This widely reported[3,4] behavior of CCDs with exposed oxide is closely related to the charge spreading phenomena seen in planar diodes.[5]

It should also be pointed out that it has been reported that there is a wide range of interface charge for which complete transfer across a gap can be achieved, regardless of electrode separation.[6] This analysis did not properly include the effect of wells which arise in the gaps at high levels of interface charge (or low substrate voltages) which can result in a considerable loss. If the size of the gap is increased, then the charge in the gap, Q_{TOTAL}, will be more effective in controlling the potential in the gap region (due to smaller fringing fields from the adjacent gates) and the loss from the barriers and wells will become even more acute. Our results, therefore, show that transfer across gaps depends upon the relative values of Q_{TOTAL} and the substrate voltage, and becomes even more critical for large gaps. This critical dependence imposes severe constraints on device passivation and threshold stability. Therefore, a resistive sea or an overlapping gate structure is needed to control the gap potential and thus eliminate the barrier and well problem. A more detailed analysis follows of how the barriers and wells result in loss.

B. WELLS

For an n-channel device, when the off gate-to-substrate voltage is too small (or equivalently the substrate voltage is too low relative to Φ_{fs} due to the charge in the gap region, Q_{TOTAL}), the device will suffer a charge transfer loss which is due to wells. These wells exist between the transferring electrode and the one preceding it. The loss which results from the wells can be considered to consist of two parts, a fixed loss and a proportional loss. The fixed loss is simply the retention of charge in the wells and can be eliminated by use of an fz in much the same way as the fixed loss from surface states is eliminated. The proportional loss results from the variation in the amount of trapped charge with a change in the size of the signal charge packet. Unfortunately this proportional loss does not decrease with use of an fz. In fact, for very large wells the loss becomes nonlinear and the transfer inefficiency actually degrades with an increase in fz.[7] This nonlinear loss due to the wells is in many respects similar to the barrier loss which will be discussed in the next section.

In Figure 7 the loss per transfer, L_L, is shown as a function of increasing fz for a 100-bit serial register (3-phase, 0.4- by 5-mil electrodes) for two different substrate voltages. The curve labeled "Operation without Wells" is for the substrate bias set for optimum operation. The other curve is with the substrate bias set at a more positive voltage so that wells appear in the gap regions. The dashed lines in these two curves represent the proportional loss which remains when sufficient fz is used to eliminate all fixed loss (approximately 15 percent). The difference between the measured curves and the dashed line is the fixed loss. For operation without wells, the fixed loss is due to surface states; however, for operation with the wells, the fixed loss is much greater and is caused by the trapping of the signal charge in the potential wells in the gaps. It should also be noted that the proportional loss for operation with wells is over an order of magnitude higher than operation with optimum substrate bias. This increase in loss is due to the dependence of the amount of charge in the wells on the size of the transferring charge packet.

It has also been observed that the amount of charge retained in the wells decreases with increasing fall time of the clock drivers. This dependence is expected, because with longer fall times less charge remains under the transfer electrode when the transfer clock voltage is off. Since the wells do not form until the transfer clock is off, less charge is available to be trapped in the wells.[8]

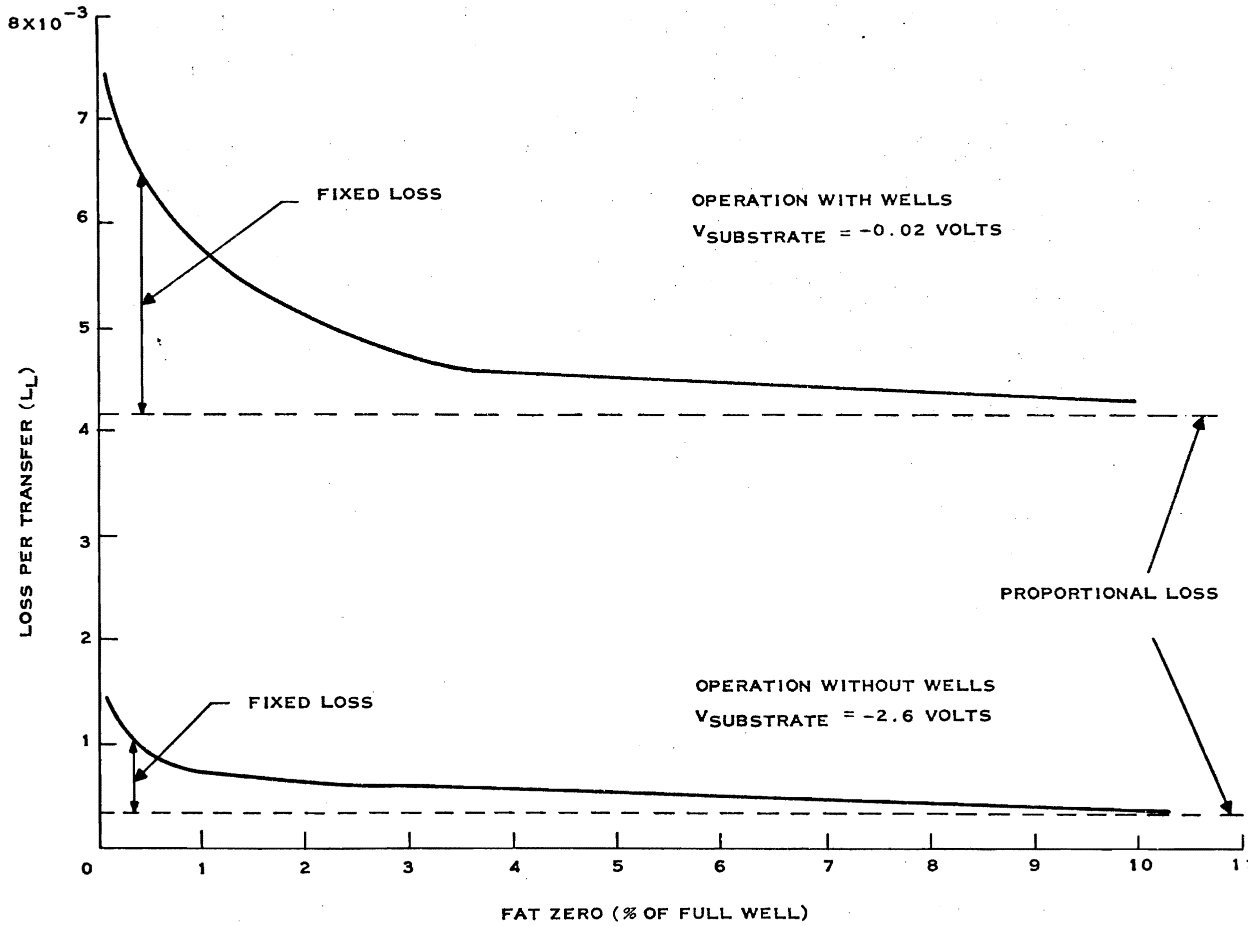

Figure 7. Loss per Transfer versus Fat Zero for a Device with and without Wells

C. BARRIERS

When the substrate voltage is too negative, it is possible for barriers to appear in the gap region. The loss which results from these barriers has several distinctive characteristics, which can be attributed to the signal amplitude dependence of the barrier height. For input signals lower than a certain threshold level, the loss due to barriers is very small; however, as the signal is increased above this level, the output signal level has additional pulses added to the end of the pulse train while the remaining pulses increase only slightly in amplitude. In many respects this dispersion makes it appear as if the device has only a very small dynamic range.

The analysis of loss due to the barriers is interesting because it is an example of a nonlinear loss. Since a nonlinear loss has a dependence on signal amplitude, the usual method of measuring loss (leading and trailing edge loss) is inadequate and an incremental technique was therefore employed. This technique linearizes the loss at a given signal amplitude, N_o, by measuring the loss in an incremental increase, ΔN, in charge above the background level, $N_o + \Delta N$.

Since the background charge, N_o, is continually being transferred through the device, an amount of charge $\epsilon(N_o)N_o$ is always left behind. When the incremental signal, ΔN, is added to the background level the signal charge, $N_o + \Delta N$, has a loss $\epsilon(N_o + \Delta N)(N_o + \Delta N)$. The net loss from the incremental signal, $L_{\Delta N}$, is the difference between the loss with and without the signal charge which is,

$$L_{\Delta N} = \epsilon(N_o + \Delta N)(N_o + \Delta N) - \epsilon(N_o)N_o \qquad (9)$$

If $\epsilon(N)$ is expanded and only the lowest order terms are kept ($\Delta N \ll N_o$) the loss, $L_{\Delta N}$, can be written as

$$L_{\Delta N} \approx \epsilon(N_o)\,\Delta N \qquad (10)$$

Therefore by measuring the loss in an incremental signal, ΔN, in excess of a background charge of N_o, the fractional loss per transfer, $\epsilon(N_o)$, of a charge packet of size N_o can be obtained. The subscript on N_o will be dropped in remaining considerations so that the nonlinear loss parameter is given by $\epsilon(N)$.

In Figure 8, $\epsilon(N)$ as determined by the incremental technique is plotted versus signal amplitude, N, where N is the fraction of a full well. This curve was taken when the device was operating with the substrate at a voltage more negative than the optimum

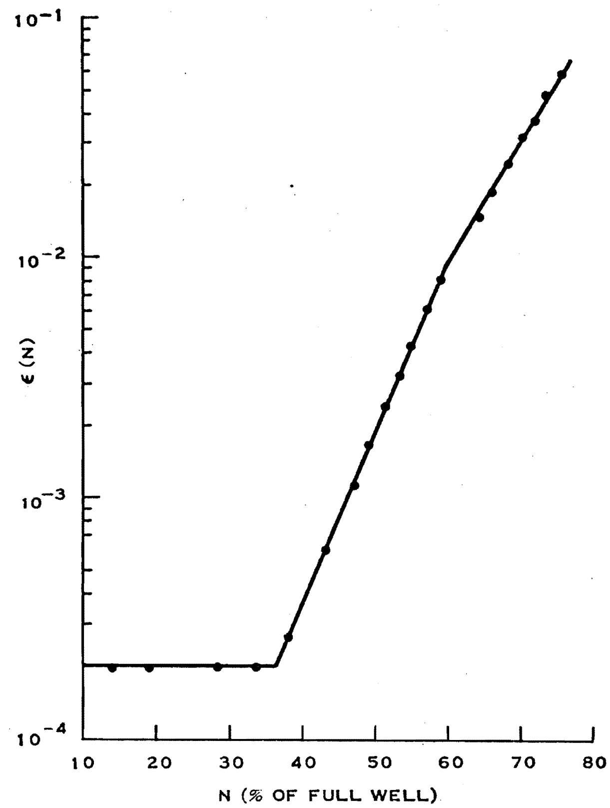

Figure 8. The Nonlinear Loss Parameter, $\epsilon(N)$, for a CCD with Barriers

value. The loss in Figure 9 is characterized by three distinct regions:

Region 1	$0 \leq N \leq 0.36$	$\epsilon(N) = 2 \times 10^{-4}$	(11)
Region 2	$0.36 \leq N \leq 0.6$	$\epsilon(N) = 6.1 \times 10^{-7}\, e^{16.2N}$	
Region 3	$0.6 \leq N$	$\epsilon(N) = 1.0 \times 10^{-5}\, e^{11.5N}$	

These three regions can be understood if reference is made to Figure 9. For a small charge (Region 1) the difference in surface potential between the transferring and receiving wells yields a large potential gradient in the gap region which suppresses the barrier. However, as a large charge is transferred, the difference in surface potentials between the two wells allows the formation of a barrier which results in retention of a portion of the charge. The increase in barrier height with signal yields the exponential increase in loss seen Regions 2 and 3. Numerical solutions of the two dimensional Poisson equations have been made which qualitatively support this model.

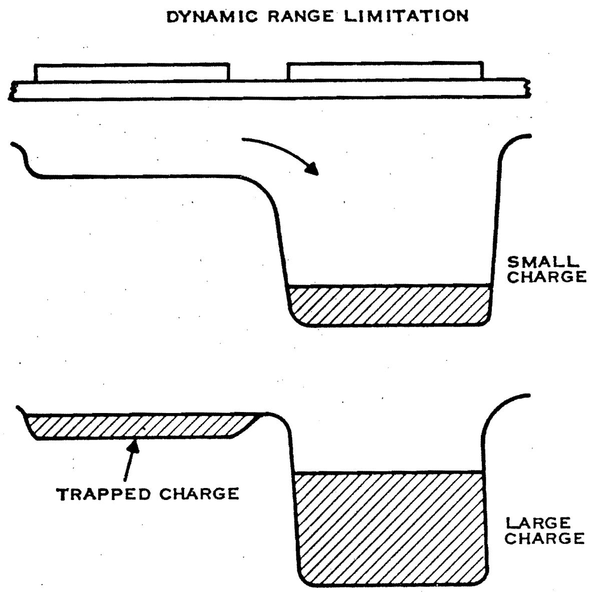

Figure 9. Illustration of How a Small Charge Can Transfer without Barriers, while Barriers Will Appear for a Large Charge

With this determination of $\epsilon(N)$, it is possible to calculate the dispersion of a signal charge as it transfers down a device. However, to make this calculation it is necessary to simulate the operation of a CCD with a computer program. For a transfer (at time t_o) from the i^{th} gate to the $i + 1$ gate the amount of charge remaining in the i^{th} well after a transfer (at time $t_1 = t_o + 1/3f_c$) is

$$N_i(t_1) = \epsilon[N_i(t_o) + N_{i+1}(t_o)]\ N_i(t_o) \qquad (12)$$

In Equation (12) the inefficiency parameter $\epsilon(N)$ is evaluated at $N = N_i(t_o) + N_{i+1}(t_o)$ because it is the total amount of charge in the $i + 1$ well at the end of transfer which determines the height of the barrier. This expression is correct as long as $\epsilon(N)$ remains small. For very large signals ($N > 0.8$), because of the difficulty in measuring such a large loss in the differential measurement ($n\epsilon > 30$), it is not even possible to evaluate $\epsilon(N)$. However, because the loss is so large, a large signal will be quickly attenuated to a lower value and only a few stages near the input will be involved in transferring large charge levels. A calculation of the dispersion is therefore essentially independent of the modeling of the very high loss transfers. The dashed lines of Figure 10 are the calculated output after 300 transfers for input signals of seven pulses with three different amplitudes, 0.27, 0.57 and 1.0. Also shown in this figure as solid lines are the experimentally obtained results for the same conditions used in the calculation. The agreement is excellent and thus demonstrates the accuracy of the incremental method of obtaining the nonlinear loss parameter. It is important to note that all of the characteristics of a barrier loss are predicted by the $\epsilon(N)$ of Equation (11), and in particular demonstrates that the dynamic range limitation is only due to the nonlinear characteristic of the transfer efficiency.

V. CONCLUSIONS

To characterize properly the transfer loss in a charge-coupled device, it is necessary to determine more than the transfer inefficiency, ϵ, at one signal level. The CCD loss mechanisms can be grouped into three basic types of loss: fixed, proportional, and nonlinear. Methods of measurement and examples of all three types of loss have been given. The more detailed characterization techniques which have been presented make possible a deeper understanding of the limitations of a given device. In using these techniques, several interesting results have been obtained. The fixed loss from surface states has been shown to be eliminated entirely by use of a fat zero and a method for obtaining the size of this fat zero has been given. Also, a dynamic range limitation which has been found in devices with exposed gaps, when operated at high substrate voltages, has been found to be due to barriers which give rise to a nonlinear loss. A phenomenological model has been devised which predicts the dispersion due to this barrier loss and comparison with experiment yields excellent agreement. Finally, in contrast with previous analysis, it has been found that at a given substrate bias zero loss transfer across gaps is possible only for a very narrow range of charge density in the gap region. This requirement places unrealistic constraints on device passivation and threshold stability. Therefore, these results demonstrate the necessity of controlling the gap potential using a technique such as a "resistive sea" or an overlapping gate structure.

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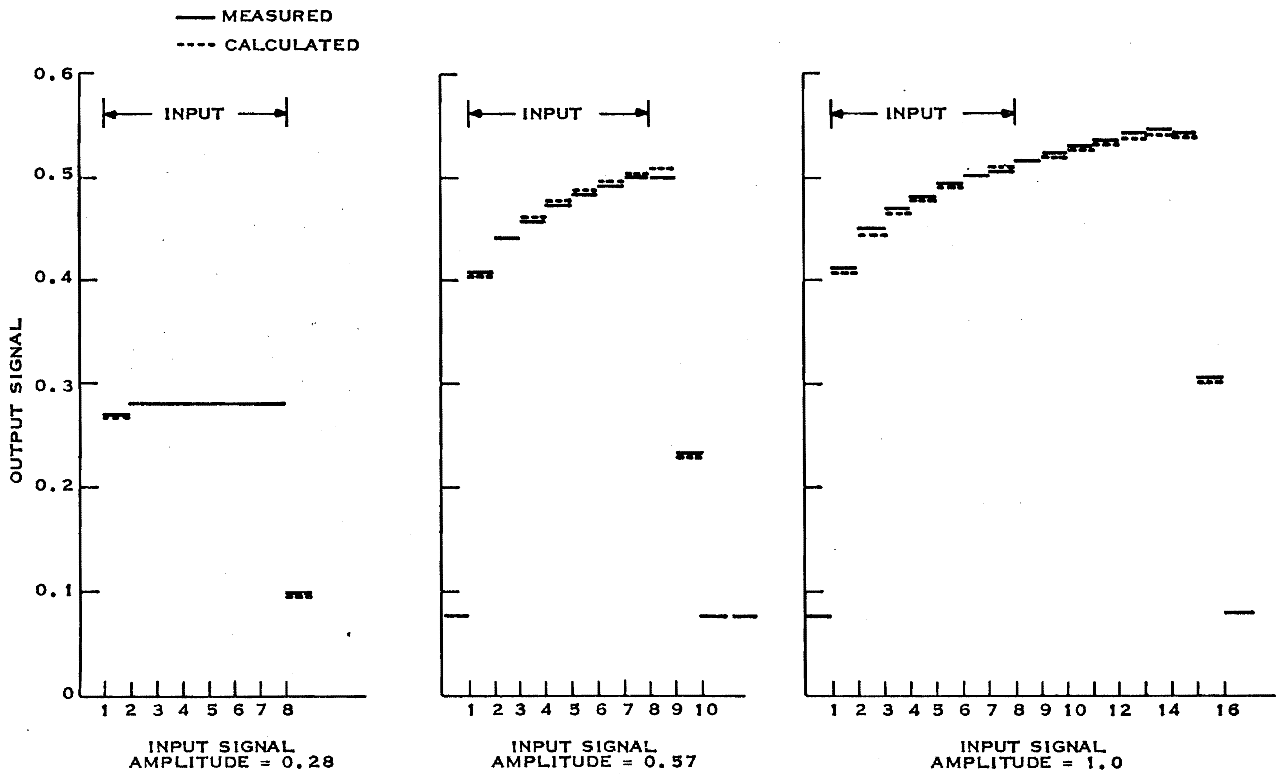

Figure 10. Calculated and Measured Dispersion After 300 Transfers for a CCD with Barriers

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