AN APPRAISAL OF CURRENT PREDICTIONS OF CCD PERFORMANCE

Include on chip logic
(2 level & phase poly p doped p silicon)

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ABSTRACT

This paper is a review of some of the predictions and measurements of parameters which characterize CCD performance.

INTRODUCTION

Since today's CCDs are becoming essentially subsystems that consist of much more than just identical charge transfer electrodes, any discussion of their performance must take this and their application into account. The free charge transfer inefficiency is, of course, fundamental but is really only important in determining when the transition from SCCD to BCCD is required for high frequency operation. The effect of interface or bulk states on the transfer inefficiency is an important effect that can be characterized experimentally but cannot, at least in magnitude be predicted theoretically.

The use of CCDs in analog subsystems requires predictions of frequency response, dynamic range, dc shifts and linearity. In a simple analog delay application, the transfer inefficiency can be converted into the well-known frequency response equation, although certain approximations are involved in this. In devices such as split-electrode filters, the effects

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of a known and constant transfer inefficiency can be compensated for. The noise and dynamic range of an analog CCD are important parameters but any calculation involves analysis of the input, transfer and signal detection effects. The thermal generation of charge is an important defect but is both sensitive to the mode of operation of the devices and is often spatially dependent, which confuses the predictions. Linearity of transfer function is crucial in many applications but there are few calculations of its magnitude beyond first order estimates.

Specific devices have specific performance parameters. For example, the use of charge-coupled split-electrode filters raises the question of the accuracy with which a required impulse response can be realized. Comparable performance parameters might be modulation transfer functions in imaging devices or operating margins in memory devices.

Most of the above parameters have now been evaluated at some level of accuracy, and the tools are available for sophisticated evaluations, if necessary. What typically are missing are detailed and precise measurements to compare with specific theoretical predictions.

TRANSFER INEFFICIENCY

There are many aspects to transfer inefficiency. The basic calculations of free charge transfer have been done by many people[1] and the closed form analytical solutions to the problem are in reasonably good agreement with each other. Even the use of the depletion approximation in BCCDs does not introduce significant inaccuracies.[2] The interface state trapping effects although dominant are less well defined with respect to both their effects in the area of the channel "wetted" by the bias charge and at the edges of the transfer electrodes. The effects have not been modeled precisely at this time. Unfortunately there is a major problem in interpreting the results of any modeling because we can only guess at the values of capture cross section near the conduction band edge (for n-channel devices). The result of G-V measurements only give accurate values of capture cross section for the opposite polarity substrate to that which is used for the CCD. Hence there is a large assumption in using numbers taken from these measurements.[3,4] Careful measurements with a few transfer electrodes might permit independent evaluation of this important parameter.

Bulk traps are of course significant in BCCDs but with single energy levels and constant capture cross sections the theory is cleaner,[5] although the limiting case of a few electrons per charge packet has not been worked out rigorously.

The effects of transfer inefficiency on the frequency response of a CCD has been rigorously derived[1,6,7] on the assumption of a constant transfer inefficiency. In practice this is not true and small discrepancies between the theoretical and measured curves have been seen.[7,8] This will certainly arise from nonlinear "edge effects" due to nonlinear spreading of charge packets and a nonuniform distribution of surface states or traps as one approaches the channel edge or the oxide interface, respectively. Pulse measurements show quite clearly that there are fixed, proportional and nonlinear transfer inefficiency components.[9,10] The nonlinear effect, arises from the emission time constants of the states or traps and gives rise to a transfer inefficiency that is dependent on the preceding signal or lack of it.

DARK CURRENT

Actual densities of traps and interface states, which determine the magnitude of the dark current in CCDs, are entirely process dependent. However, given these numbers the magnitude of the dark current generated in an ideal fully depleted CCD is theoretically predictable given all the other necessary dimensions, voltages applied to the device and the capture cross sections of midband traps and states, which are reasonably well known.[3,4] However, the real problem lies in predicting the dark current in real devices, where bias and signal charge can fill the midband states and suppress the generation from bulk traps in BCCDs or interface states in SCCDs. Some specific calculations and measurements of generation rate have been made.[11] However, each particular device operated in a specific way must be considered separately. In addition, there are uncertainties in the trapping and retrapping effects of bias charge, signal charge and thermally generated carriers, which need to be theoretically evaluated.

NOISE AND LINEARITY IN ANALOG DELAY DEVICES

Predictions of signal-to-noise ratios in analog CCDs have been made[1.12] and actual numbers measured. The discrepancy in overall signal-to-noise ratio is only 10 dB, although when a linearity constraint is added, the peak signals may need to be reduced.[13] All the expected noise sources have been well characterized in two papers[12,13] and mostly conform to the theoretical predictions. The interface state noise effect in an SCCD has the expected $(1 - \cos 2\pi f/f_c)$ form due to the correlation of the transfer noise between neighboring packets. Even its dependence on the size of the charge packets conforms to expectation of the edge effect. Input noise was measured[11] and found to be three times greater than the theoretical value of 220 electrons (2/3kTC) per charge packet although other work[14] showed, that at least for the injection of small charge packets, that the equivalent noise charge was 1.1 kTC or 1.7 times the theoretically predicted value. No satisfactory explanation exists for these discrepancies, other than noise on clock-lines or the lines biasing the input electrodes, or "splashing" as clocks turn on or off at the input.

Noise at the output MOSFET is largely an empirical quantity, although it would be correlatable to interface states under the gate. Quite low values have been measured, 50 electrons[12] and <150 electrons[14] for a regular surface MOSFET and <50 electrons for a buried channel MOSFET.

The linearity of different input structures is calculable to a first-order in terms of MOSFET currents or depletion capacitance but second and third order effects[15] seen on "fill and spill", and differential channel input structures have not been discussed theoretically.

PERFORMANCE OF SPLIT-ELECTRODE FILTERS

The split-electrode charge-coupled filter provides a good example of a functional device with wide application. The parameters that one wishes to predict are the linearity, the noise and the accuracy with which a given transfer function may be realized. The way in which these trade-offs can be made has been well presented.[16] The prediction of the transfer function is numerical and automated procedure that can be done with as much accuracy as required but must include the quantization of the tap weights as imposed by automated mask making facilities. For example, it has been shown that in a 63-tap low-pass filter with a channel width of 750 μm and 600 quantization levels that the differences of the measured curve from the "rounded off" stop-band response are less than those of the "rounded off" stop-band responses from the optimum. Hence the random errors must have a mean on the order of 1 in 1200, i.e., 0.1%. However, the passband response indicates correlated error on the order of 1% in the filter of unknown origin.

The effects of transfer inefficiency on the required filter function are normally small because the effects are correlated from one charge packet to its immediate neighbor; however, the resultant effective tap weights h_n' are related[17] to the original weights h_n by

$$h_n' = \sum_{j=0}^{n-1} h_{n-j} \binom{n-1}{j} (\rho\varepsilon)^j (1-\rho\varepsilon)^{n-j}.$$

Another way to look at the effects of transfer inefficiency is via the normal frequency response equation, which will create an attenuation that increases with increasing signal frequency.

The cause of nonlinearity in a transversal filter is the variable depletion capacitance. This effect can occur in two areas. If a linear (voltage-charge) input is used, then the charge stored in the depletion capacitance under the sensing electrodes is not detected and creates distortion. This effect can be eliminated by using an input method which sets the surface potential in a metering well equal to the input signal voltage. Nonlinearity also arises during detection of the charge packets if the potential of the sense nodes is allowed to vary during sensing. This can be prevented by using the feedback of an operational amplifier. Without this technique and a substrate doping of 5×10^{14} cm^{-3}, we would expect a differential capacitance ratio of $\sim 1 \times 10^{-2}$/volt. Results show that linearity has been controlled in the range 40-60 dB. Third order effects limiting the very small residual nonlinearities are not understood at this time.

Noise in transversal filters can in principle be predicted accurately[17] although there is considerable uncertainty in the parameters that are used in the calculations. The input mean square noise charge/packet is $2kTC_e/3$ and will be filtered by the transfer function of the filter. The total noise charge induced on the N split electrodes will be therefore

$$Q_{is} = \left(\sum_{n=0}^{N-1} h_n^2 \right)^{1/2} \left(\frac{2kTC}{3} \right)^{1/2} .$$

Surface state noise induced on the sense electrodes can be calculated[17] to be

$$Q_{bs} = qA_e N_{ss} kT \, p \, \ln 2 \sum_{n=0}^{N-1} \left(2h_n^2 - h_n h_{n-1} - h_n h_{n+1} \right)^{1/2} .$$

A more important source of noise is that arising at each split. At equilibrium, the equivalent circuit consists of two capacitors of value $(1-h_n)C_e/2$ and $(1+h_n)C_e/2$ connected between the sense electrodes and giving an effective capacitance of $(1-h_n^2)C_e/4$. The total noise charge Q_{se} arising from this source is therefore

$$Q_{se} = \frac{1}{2}\left[kTC_e \sum_{n=0}^{N-1}\left(1 - h_n^2\right)\right]^{1/2}$$

If a reset technique is used on the sense electrodes then the potential of each sense electrode is set twice and the net noise after differencing will be $4 \times \frac{2}{3}\, kTC_{se}$ where C_{se} is the capacitance of the sense electrode to other electrodes, to the substrate via the the thick oxide and to the substrate via the depletion capacitance under the thin oxide. This noise component Q_{rs} is given by

$$Q_{rs} = \left(\frac{8}{3}\, kTC_{se}\right)^{1/2} .$$

In a 55-tap filter, $C_{se} \sim 20$ pF and the net effective signal charge induced on the sense electrodes after differencing is 12 pC, giving a signal-to-noise ratio of 92 dB from this noise source. The inclusion of Q_{se} and assuming that $NC_e \approx C_{se}$ and that most $h_n = 0$ will reduce this noise figure to $\sim$86 dB. So far, signal-to-noise ratios of 62 dB and 75 dB have been measured on a 63-tap filter[16] and a 500-tap filter,[17] respectively. Correlated double sampling improves these numbers by partially removing the reset noise but the reasons for them still being below the theoretical limit is unclear. Possibly the use of on-chip output circuits will improve them.

CONCLUSION

I have tried to point out topics where precise theoretical predictions of CCD performance in important areas of application are lacking. However, it must be remembered that so far the rate of progress of the CCD art has been largely controlled by increases in design cleverness and to some extent by fabrication technology. More precise theoretical predictions of CCD performance may now be appropriate as a way of realizing higher performance or of reducing silicon area and increasing levels of integration.

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