A Surface Charge Correlator for Signal Processing*

J. J. Tiemann R. D. Baertsch W. E. Engeler
General Electric Corporate Research and Development

ABSTRACT Charge transfer devices (CTD's) represent a major advance for analog signal processing. Transversal filters with fixed tap weights are naturally suited to these devices, and they can perform any linear process on a (sampled data) input signal. A cross-correlator performs the same function as a transversal filter, but the tap weights are electrically variable. Thus a correlator can be programmed to perform essentially all linear processes. Surface charge techniques have been used to implement a cross-correlator module in which the tap weights are restricted to values of plus and minus one. This compromise permits most of the advantages that characterize the fixed weight structure to be retained, and the disadvantage of fixed taps can be overcome by using a weighted binary code for the tap weights and a separate channel for each binary digit.

The experimental device, which contains 32 stages, was implemented in p-channel MOS technology and was designed to operate at 4 MHz. Some experimental test results are presented, and some specific applications are discussed.

INTRODUCTION

Charge transfer devices (CTD's) represent a major advance toward applying the strengths and benefits of integrated circuit technology to analog signal processing. A number of CTD devices have been emerging recently, but a discussion of this subject is beyond the scope of this paper. In general, these devices contain a large number of charge storage capacitors and control gates which are clocked with appropriate wave-forms so that charge packets representing the sampled data values of an analog signal can be controllably moved around on the surface of a silicon integrated circuit while being maintained virtually intact.

Probably the most natural structure for signal processing CTD's is the transversal filter or multi-tapped variably weighted delay line. The transversal filter can be implemented with a serial transfer CTD in which the charge packets are passed from stage to stage along a linear path. At each stage, the amount of charge is non-destructively measured, and this measurement is

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used to define the output from the "tap" at that point. Note that the measurement in no way removes any charge from the packet and does not degrade the signal or introduce any reflections. To form a transversal filter, the tap outputs must then be appropriately weighted and summed. There are a number of techniques available for assigning specified tap weights and performing the sum over taps. The simplest method for assigning a tap weight is to divide the storage capacitor associated with each stage into two portions and sense only the charge on one of them. Summation of the charge residing on all of the selected portions can be performed by connecting all the capacitor electrodes to a common drive circuit and monitoring the drive current required to charge or discharge them. Thus, the multiplicative tap weights are determined by the location of cuts in the capacitor plates, and the addition is performed by strapping the capacitor electrodes together.(1)

The fact that CTD's can be used to implement a transversal filter is important because the transversal filter can produce virtually any linear function of an input signal. (2)

Since the transversal filter is a general purpose building block, and since it can be so easily implemented with CTD's, it is anticipated that there will soon be an upsurge in the use of sophisticated signal processing techniques using CTD transversal filters in areas where cost considerations have previously prevented their appearance.

A cross-correlator performs the same function as a transversal filter, but it can accept the tap weights as the (sampled data) values of a second input signal. That is, a cross-correlator can implement all possible transversal filters. Since the transversal filter can accomplish any linear process, it follows that a cross-correlator can implement <u>all</u> linear functions. Thus, a cross-correlator is a truly general purpose signal processing device.

Note that the method for obtaining tap weights discussed above is not suitable for a cross-correlator element because the tap weight cannot be changed. In a correlator the tap weights must be electrically determined in some manner. To implement a correlator, the input samples must first be multiplied point by point by electrically variable tap weights, and the resulting quantities must then be summed over all points. Summation can be performed in a surface charge device in the manner described above, but there is no convenient way of obtaining an electrically variable multiplicative fraction of the surface charge in a storage reservoir. Thus, there does not appear to be an ideal implementation of a surface charge correlator, and other less elegant approaches must be considered. One approach would be to implement the correlator digitally and perform the multiplications and additions with logic. Although this approach is feasible, it requires far more hardware. Not only must individual modules be used for each term in the partial products, but also the final summation, which is performed automatically in the approaches outlined above, would also have to be separately implemented. In this paper, a hybrid approach will be described in which one set of signal samples is represented by a continuously variable quantity of surface charge, while the other channel is limited to binary values. Automatic summation is provided as described above by connecting the output electrodes together. Thus, most of the efficiency of analog methods is retained, and a convenient interface to the digital world is also provided. Although limitation to only two tap weight values may seem to be a serious problem, it can be overcome with the use of additional correlator channels. Suppose, for example, that the analog signal is fed in parallel to a number of correlators and that the first is assigned weights of ± 1, the second, weights of ± 1/2, and so on in descending powers of two. If the outputs of these channels are all summed together, then every signal sample can be assigned an arbitrary weight by sending the respective binary digits of the desired binary coded tap weights to the respective correlator channels. Usually four to eight channels would be required to achieve the tap weight accuracy appropriate for typical applications.

The magnitudes of the tap weights could be set either by combining the outputs of devices having unit magnitude tap weight in a resistor ladder, or the geometry of the charge reservoirs of each channel could be made to correspond to the desired binary weights. A combination of these two methods could also be employed.

There are at least two approaches for obtaining binary controlled tap weights. In one approach, the electrodes associated with a particular cell are connected to either of two drive lines by series switches, (such as MOSFETs) only one of which is turned on at a time. (See Fig. 1) In this way, the added capacitance due to the signal charge will appear as a load on either of the two output lines.

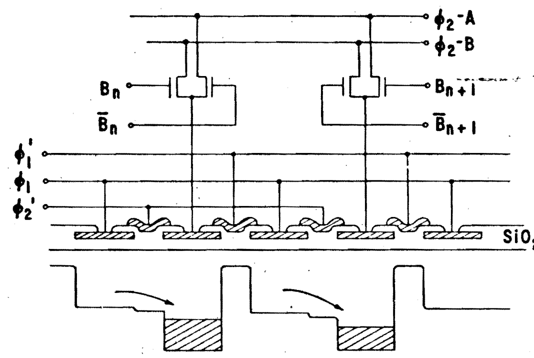

Fig. 1 Schematic of a method for obtaining binary tap weights using a serial charge transport structure. The surface potentials during charge transfer are shown.

Another approach is to use a Surface Charge Transistor structure (3) as the basic CTD element and use a switch to control the transfer gates. In this way, the direction of charge transfer in each cell can be controlled by the binary signal, and the charge can be directed to either of two output regions within each cell. As was mentioned above, summation over cells can be automatically achieved by using common electrodes for all cells in the system. In this case, two readout regions are needed within each cell, and the charge must be held between them prior to the readout operation. Tap weights of plus and minus one are derived by directing the two output signals to the non-inverting and the inverting inputs of a differential op-amp respectively.

During the first part of each readout cycle, the surface charge is held in the center region of the cells by a holding electrode (electrode "C") which is placed over the gate oxide in the center of each cell. There are also two other insulated electrodes ("A" and "B"), which serve all of the cells in the structure, located on either side of the storage cells as shown in Fig. 2.

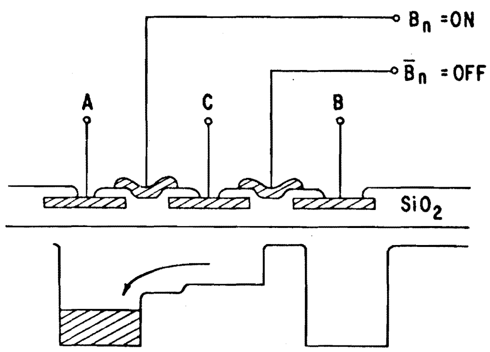

Fig. 2 Schematic of a second method using the Surface Charge Transistor. Charge is stored under a central reservoir and transferred to the A and B electrodes under control of the transfer gate.

During each period, the charge is transferred within the cell so that a capacitively coupled (non-contacting) readout can be achieved. This is accomplished by first charging the A and B electrodes to a potential that is more attractive than that of the central region and then disconnecting them from the charging circuits. And, although it is now energetically favorable for the charge to transfer to either of the two outer regions, this transfer is prevented by two gates which lie between "C" and these outer regions. The potentials of these two gates are controlled by the binary signal, which represents the tap weight to be applied to the charge in the cell. Only one of the two transfer gates is turned on by the binary signal, and this determines whether the charge will move toward the A electrode, or B. The motion of the signal charges toward these floating electrodes causes their potentials to drop toward ground by an amount approximately proportional to the total charge that transfers to each of them. In this way, the analog signal represented by the amount of charge stored in the cell is multiplied by the tap weight of either plus or minus one.

TEST RESULTS

An experimental structure having 32 stages has been built and tested. Although exhaustive testing of the experimental devices has not yet been completed, preliminary results are available that are very encouraging. In one test, the analog signal was held at a voltage level appropriate for a "full" bucket for 64 pulses and then at a level that produces an "empty" well for a like period of time. For each condition of the analog voltage, binary "ones" (causes readout on the "A" side) were inserted into the binary channel followed by 32 binary "zeros" (causes readout on the "B" side). The outputs on the "A" and "B" electrodes are shown in Fig. 3 along with the input signals. First the "A" signal increases linearly from zero to a maximum level reflecting the fact that each clock pulse has one more full reservoir of charge than the preceding one. After 32 pulses, all of the reservoirs are filled and binary "zeros" are entered into the binary channel. As these are entered they cause the charge in each reservoir to be taken away from the "A" side and appear on the "B" side.

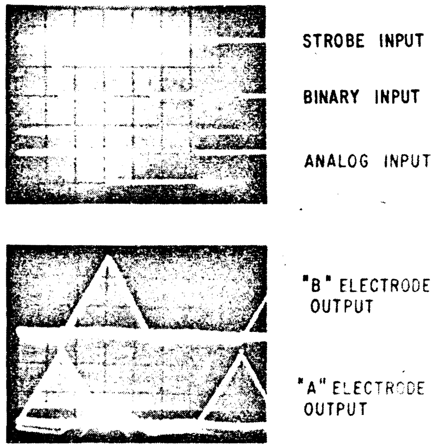

Fig. 3 Input and output signals from the surface charge correlator.

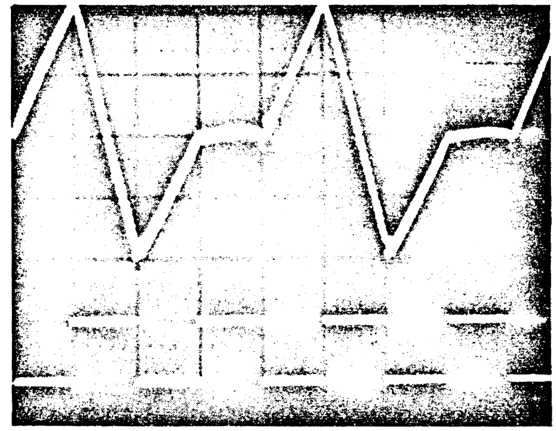

Fig. 4 Output from sample and hold amplifier. The square wave is the binary channel input.

This can be seen in Fig. 3 in the second segment where the "A" signal is linearly decreasing while the "B" signal is simultaneously increasing. After 32 "zeros" have been inserted, all of the charge is read out on the "B" side. At this point, the analog signal changes to the level for an empty reservoir, and full reservoirs are replaced by empty ones. Binary "ones" are now also being entered. Thus, even though the transfer direction is being changed back to the "A" side, no output appears on the "A" signal. When the "B" signal has decreased to zero, all of the reservoirs are empty and they are attempting to transfer to the "A" side. At this point, "zeros" are again inserted into the binary channel, but since the reservoirs are empty, no output appears on either "A" or "B". When these two signals are appropriately sampled and held and are fed to the output differential amplifier, the (much cleaner looking) waveform shown in Fig. 4 results.

This double polarity signal can be recognized as the correlation function of two square wave signals with periods in the ratio of 2-to-1.

SOURCES OF ERROR

A number of different sources of inaccuracy are expected in the device described above. These include

1. Input and output non-linearities due to the voltage variation of the depletion capacitances of the charge storage reservoirs. These non-linearities, together with an additional non-linearity inherent in the charge transfer operation itself, may cause a small cross-modulation effect. Accurate data on this problem is not available at present, but the linearity of the output signal shown in Fig. 3 and 4 indicate that this is not a serious problem. The overall variation of the output voltage versus the input potential for the basic charge storage element is shown in Fig. 5. At low voltage, the data becomes non-linear because of the voltage

variation of the depletion capacitance of the input reservoir. In the region where the reservoirs are nearly empty, the output again becomes non-linear. In this case, the non-linearity is caused by the variation of the surface Fermi-level energy with respect to the band edge. There is a rather broad range between these two extremes where the linearity is acceptable.

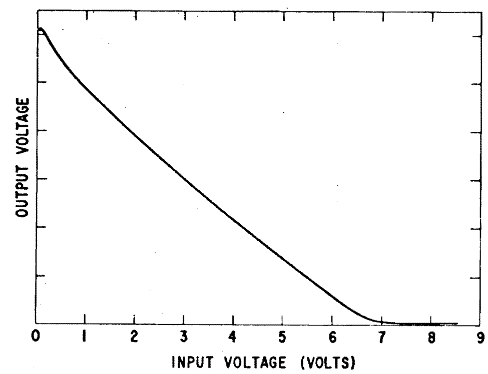

Fig. 5 Input-output characteristics of the basic charge storage element of the correlator.

2. Variations in the geometrical areas of the individual charge transfer cells themselves will appear as a modulation of the tap weights associated with the cells. This error source is essentially the same as that encountered in determining the resistance ratio of two diffused resistances on the same chip, and by analogy with that experience, it is expected that these variations can be held to less than 1%. These modulations are not time dependent, and it would be possible in some instances to take them into account.

3. The overall level of thermally generated leakage current limits the storage time of the analog signal samples. This effect is common to all CTD devices, and it varies considerably with the specific processing used. This effect was studied in the experimental structure discussed above. Although no special processing steps were specifically introduced to remove recombination centers, the observed storage time was approximately one second at room temperature. At this level, useful delay times of several tens of milliseconds would be permissible, and systems involving several tens of thousands of cycles between refresh operations could be built. If better processing had been employed, we expect that useful performance could be obtained at temperatures up to about 70 degrees C.

It appears at present that none of the above mentioned sources of error or non-linearity will exceed 1%, and it seems unlikely that the geometrical error will be much less than this figure. Hence an overall input accuracy of about 1% seems to be a reasonable expectation.

DYNAMIC RANGE

For the reasons discussed above, the dynamic range at the input seems limited to the vicinity of 40 dB. The output dynamic range may be much greater than this if large numbers of reservoirs are present. In this case, the input errors can be expected to average out, and the dynamic range will be limited by the characteristics of the output itself. If the limiting factor is the noise of the output differential amplifier, the dynamic range will be given by the ratio of the noise voltage to the maximum signal voltage. For a signal bandwidth of a few MHz, input noise levels of 10 to 100 micro-volts are easily achievable, whereas the output signal itself will be of the order of ten volts. This implies that an output dynamic range of 100 dB or over could be achieved. At present, a value of 66 dB has been measured. This would be expected to improve as larger systems are formed. Even though the output capacitance increases as more reservoirs are added, the output voltage does not decrease because more signal charge is added in direct proportion to the amount of added output capacitance. Thus, the maximum output signal stays the same while the noise and error levels get smaller.

APPLICATIONS

It is not possible to list all the potential signal processing applications for a general purpose device such as a programmable cross-correlator, but some applications require one or more of the specific features provided by the correlator described above. The programmable aspect of this device is advantageous in a number of specific applications such as:

1. Adaptive Systems
2. Multiplexed Systems
3. Secure Systems

In adaptive systems, the parameters of a particular signal processing function are chosen on the basis of outputs from previous processes. For these applications, it is essential that a programmable processor be used. In multiplexed systems, the advantage of programmability is in cost. With a programmable element, only one piece of hardware is required to perform an entire repertoire of processing functions on many different input signals. In some cases, the tap weight function can be computed from highly compacted data, and in other cases individual functions may be stored in ROM. In either case, the cost of computation or storage of the tap weights will be less than the cost of separate transversal filters. In secure systems, the ability to change codes quickly and automatically is of obvious value. There are also a number of applications where the limitation to binary tap weights is not important, and in these cases the device described above may be efficient enough to compete against other approaches even when these other approaches are dedicated to the specific task. One example of this class of applications is a matched filter for a p-n sequence. Similarly, the computation of one and two-dimensional Hadamard-Walsh transforms appears very attractive when implemented with elements of the type described.

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