The Inception of Charge-Coupled Devices

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IT WOULD seem that the authors of the papers in this special issue have a very heavy responsibility. Much has been written about the mental processes that lead to innovation but this is one of the rare times that a group of people who themselves have participated in the act of innovation have been asked to shed some light on the factors which contributed to the generation of a new concept. It is not difficult to document the apparently important features; they have been told many times before. Indeed the telling and retelling with embellishments of "the day that etc." gradually takes on a ring of authenticity that eventually becomes fact in itself. On this occasion, however, we shall try to analyze once again just exactly what did transpire, with the full understanding that with all the best effort at objectivity, it may still not be an accurate account of the subtle interplay between people that certainly played a most important role in our own work.

The charge-coupled device concept is one that is basically a structure that called upon existing technology and was stimulated by the analogous work that preceded it in magnetic bubbles. All the ingredients necessary for the innovation were found within Bell Laboratories. The now well-known work at the Philips Eindhoven Laboratory by Sangster [1] and his colleagues on the Bucket Brigade was unknown to us. The importance of the Bucket Brigade as a member of the family of charge transfer devices is well recognized, and we want at this point to recognize the important contribution to device technology that has been made by the work at Philips.

In late 1969, the device area of Bell Laboratories was strongly oriented towards innovation and exploratory development of new devices. Strong efforts were being directed towards such fields as IMPATT diodes, GaAs lasers, nonlinear optics, solid-state lasers, holography, Gunn diodes, magnetic bubbles, and the silicon diode array camera tube. Of particular interest was the work on magnetic bubbles. It was apparent that a radically new approach to signal processing was being brought into existence.

Those of us who were working on semiconductor integrated circuits looked at the work in magnetic bubbles with some awe. In the magnetic bubbles it seemed that a new class of devices was in the offing in which there was a very natural and appealing way of storing and manipulating bits with a one-to-one correspondence to the digital format. It could be argued that semiconductor integrated circuits, important as they were, had not yet broken away from the circuit concepts that had evolved through the use of discrete components. The late Jack Morton, who was at the time Vice-President of the Electronics Technology area, was a strong proponent of the magnetic bubbles program but felt, at the same time, that surely there must be some analogous devices using semiconductors. He was both persuasive and Vice-President, so his admonitions to develop a semiconductor bubble-type device received rather close attention. The encouragement from management was there. Indeed, it was more than encouragement at times and it seemed that unless we came up with something comparable, future funding of the exploratory programs in semiconductors might be in jeopardy. Certainly this was only a perceived threat, but it does convey the atmosphere at the time.

Another very important ingredient was the development program for the silicon diode array camera tube [2]. One of us (G. E. Smith) had been deeply concerned with the material and device technology required to fabricate defect free diode arrays in silicon. These diode arrays had to have both the light sensitivity and the charge storage capability to provide an imaging device of acceptable quality for the PICTUREPHONE® imaging tube. The charge storage on individual diodes had been particularly troublesome. However, success was at hand, and it was possible to routinely fabricate hundreds of thousands of diodes on a single chip without a single defective diode. Moreover, the charge could be stored in one of these diodes for periods approaching a hundred seconds.

It was in this atmosphere that the charge-coupled device was born. During an afternoon discussion between the authors lasting not more than an hour, the structure and some preliminary ideas concerning applications of the device were developed. The train of thought evolved as follows.

First, the semiconductor analogy of the magnetic bubble is needed. An electrical dual is a packet of charge. The next problem is how to store this charge in a confined region. The method which came to mind was the metal-oxide-semiconductor (MOS) capacitor in depletion. This forms a potential well at the surface into which one can introduce charge (or not) to represent information in the same way that the presence (or absence) of magnetic bubbles on a site formed by a permalloy pattern represents information. The last problem was to find a way to shift the charge from one site to the next, thereby allowing manipulation of the information. This is solved by placing the MOS capacitors very close together in order to easily pass the charge from one to the next by applying a more attractive voltage to the receiver. This completed the basic invention, and the at-

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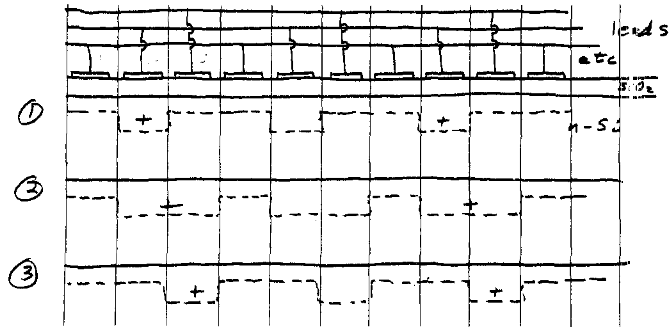

Fig. 1. Reproduction of the notebook sketch of the first three-phase charge-coupled device.

tendant frills and possible applications came rapidly after. The first notebook drawing of the device, shown in Fig. 1, depicts the basic 3-phase configuration and is still valid in describing today's device.

It seemed almost too easy and straightforward, so, having had past experience in seemingly brilliant ideas which subsequently fizzle, we allowed the idea to remain just that for a few weeks. In talking with colleagues the reaction was varied, ranging from "I should have thought of that" to lengthy lists of reasons why it would not work.

At this point we want to observe that a certain amount of arrogance is essential in carrying forward an idea. In talking about the device with others, it is surprising now in retrospect the number of people who either were quite negative and had reasons to suggest it would not function as described or claimed that it would be of little interest and no better than some already existing device. Although each of us had more than our share of ideas that were of no consequence, we had also experienced the frustration of having dropped a proposal only to have it independently brought forward successfully by someone else. Our frame of mind at this time was such that we had confidence that our idea was sound and important regardless of how negative a few of the comments from our colleagues might be.

Finally, it was decided to go ahead and fabricate a device to show experimental feasibility. In less than a week, masks were made and devices were fabricated, mounted, and tested. The photo in Fig. 2 shows the first device which consisted of a simple array of 0.1 mm × 0.1 mm MOS plates placed in a row with three-micron spacings between them. Charge was injected by avalanching the first plate, and, after a series of transfers, the charge was detected by measuring the current produced by injection into the substrate. This activity took place in October 1969.

A beehive of activity and intellectual excitement took place immediately after this. The idea was infectious and many others made substantial contributions in the weeks to follow. Dawon Kahng developed the idea of a built-in barrier under one side of a plate to make a two-phase device [3]. A three-phase device can be used for a linear device or an array in which the charge goes in one direction, but, for a serpentine memory array, a two-phase device is needed to avoid crossovers.

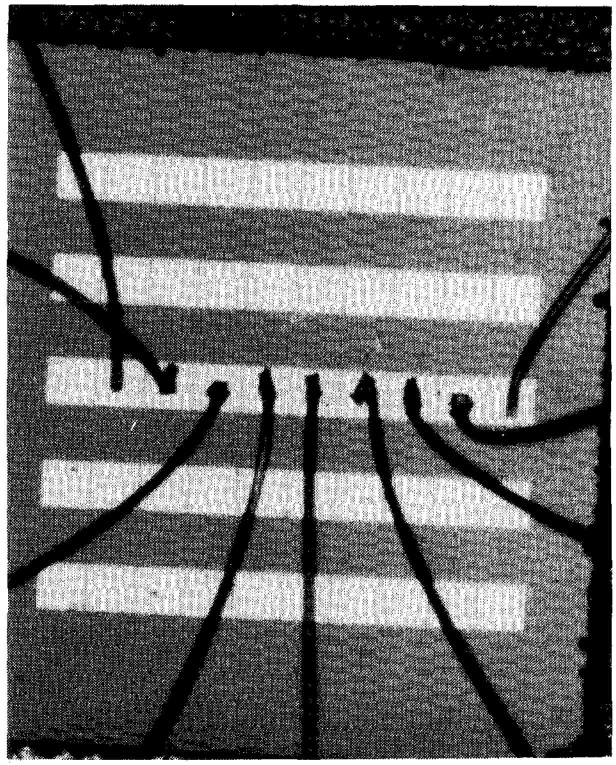

Fig. 2. First experimental array of field plates used to demonstrate the principles of charge transfer.

Eugene I. Gordon conceived of a display device in which the video charge pattern is read in serially and then injected into the substrate in a parallel manner to produce a display via radiative recombination. Harry J. Boll and C. Neil Berglund reinvented the Bucket Brigade, being unaware of F. L. J. Sangster's prior work and also recognized the importance of a fat zero. Boyle and Smith, recognizing that complete charge transfer can be limited by surface state trapping, circumvented the problem with the buried channel concept. This device uses a structure in which the charge is not stored at the semiconductor–insulator interface but in the bulk of silicon. This can be done with a special doping profile and then the complete transfer is limited by the much less numerous bulk states. Many others contributed with ideas too numerous to mention.

The first public announcement was made at the New York IEEE Convention held in March 1970. Boyle was a member of a panel discussion on the future of integrated circuits and came equipped with one vugraph showing the basic operation of CCD's. He spent less than five minutes explaining the device but many people understood immediately as evidenced by the lively discussion which followed. It was also picked up by the press and covered in several of the trade publications.

The ideas were subsequently reported by Boyle and Smith [4] in the April 1970 issue of the *Bell System Technical Journal* in which charge storage in an MOS capacitor was discussed, the basic three-phase structure described, and possible applications outlined. Storage

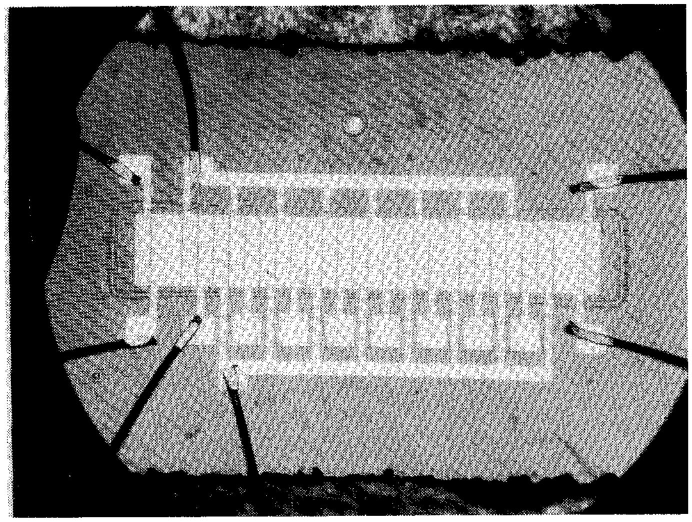

Fig. 3. The first 8-bit fully integrated device with diode inputs and outputs.

times and the three factors determining transfer efficiency were discussed; namely, the limitations imposed by surface state trapping, the limitations imposed by diffusion, and the field enhancement resulting from the change in surface potential with charge density. Overcoming the limitations by using geometrically induced fringing fields was also mentioned. Several applications were discussed in the paper. One was to use the device as a serial shift register or memory with p-n junction input and outputs. The background of bubbles naturally led to thinking of the shifting of digital information in the form of charge or no charge, but the diode array influence soon made the analog application of imaging come to mind, both linear and area. Here a parallel input is produced by light making electron–hole pairs and then the analog information read out in a serial fashion. Use of the device as an electrical analog delay line was envisioned but the full significance of this was not realized at the time and perhaps still is not. Two-dimensional arrays and logic were also mentioned.

The first experimental results were reported in a companion paper by Amelio, Tompsett, and Smith [5] in which storage times of 16 s and transfer efficiencies of 98 percent were reported.

The first regular technical paper was presented by Smith at the Device Research Conference held in Seattle that June. A paper by Tompsett, Amelio, and Smith [6] on the first device with diode inputs and outputs and integrated interconnects came out in August. This was an eight-bit device (see Fig. 3) which had a transfer efficiency of 99.9 percent at 150 kHz. The device was also used to demonstrate imaging for the first time and even though its eight element accuracy left something to be desired (see Fig. 4), the principle was established. By this time, many other workers had started work on CCD's and activity was accelerating at a high rate. A high level of activity has remained, and at this time, it appears that the device will

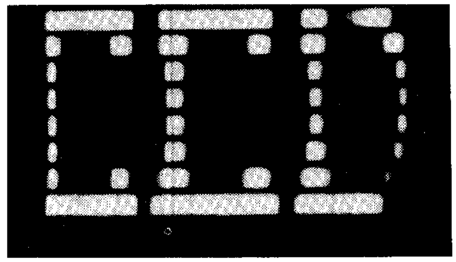

Fig. 4. Image produced by an 8-bit linear array of CCD elements. Scanning from left to right was obtained mechanically.

find a permanent place in electronic systems. Area imaging devices with the full commercial format have been demonstrated, and several area and linear devices are available commercially as are digital memory devices containing up to 16 kbits. Perhaps the most innovative applications are yet to come and will be in the field of analog signal processing.

The device can be used in a straightforward manner as an analog delay line with practical delays of tens of milliseconds. The linearity and noise characteristics match those of most active linear devices, and costs are far below any other method of obtaining such long delays. It also has the advantage of being able to change the delay simply by changing the frequency at which information is clocked along.

By feeding the output back to the input, a first order recursive filter is formed and by putting many such elements together, a general nth order filter network can be formed. Elegant methods of tapping such a delay line have been devised, and a transversal filter with over 800 taps has been demonstrated.

Another application is time compression and expansion in which information can be read in at one rate and read out at another. Using such elements, a time compression multiplexing system can be made.

Details on all of the above are now well documented in the literature[7].

Many other such analog configurations are being invented and demonstrated. It is even possible that they will stem the tide of the ever increasing encroachment of digital signal processing into the linear world. Only the future will tell.

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