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Section A

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## The invention of the CCD

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To try to indicate how the invention of Charge Coupled Devices (CCD) came about, it is necessary to describe the rampant innovations in technology existing at the time and more specifically, the stimulating creative atmosphere present at Bell Labs. First of all, it was inspired by analogous work in magnetic bubbles which was being strongly supported by the Electronics Technology Vice President, the late Jack Morton, who also demanded of Boyle that some similar device should be devised using semiconductor technology.

The bubble technology was a shift register type structure in which the presence or absence of a magnetic dipole representing 0s and 1s which were moved along by a rotating external magnetic field and which was being developed mainly for memory applications. Two other new technologies, the silicon diode array camera tube and the MOS transistor, also had important influences.

The camera tube was an array of thousands of defect-free diodes fabricated on a single chip which were accessed by an electron beam and was being developed for use in the Picturephone (Fig. 1). It was clear that an all-solid-state imaging device would be desirable. The MOS transistor was just in the early stages of development for circuit applications and much basic work had been done for understanding the metal-oxide-semiconductor capacitor.

It was in this atmosphere that the charge coupled device was born. On the 8th of September 1969, Bill Boyle and I got together in his office at Bell Labs in Murray Hill, NJ, to address Morton's

demand for a bubble-like device using semiconductor technology. In a discussion lasting not more than an hour, the basic structure of the CCD was sketched out on the blackboard, the principles of operation defined, and some preliminary ideas concerning applications were developed. The train of thought evolved as follows.

First, the semiconductor analogy of the magnetic bubble is needed. The electric dual is a packet of charge. The next problem is how to store this charge in a confined region. The method which

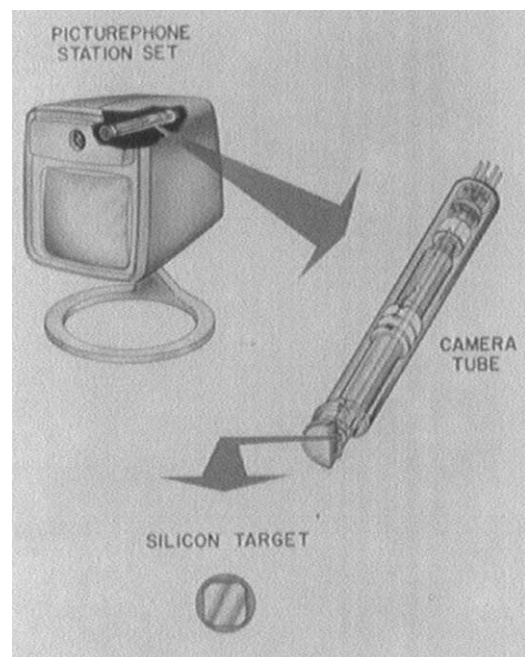


Fig. 1. The Picturephone and silicon diode array camera tube.

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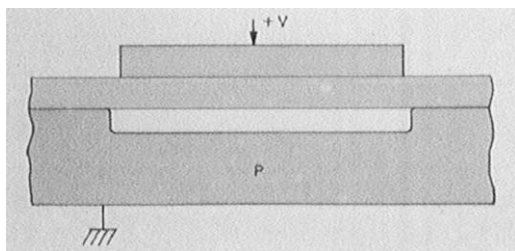


Fig. 2. The basic Metal-Oxide-Semiconductor structure with a voltage applied to the metal plate forming a depletion region in the semiconductor where charge can be stored.

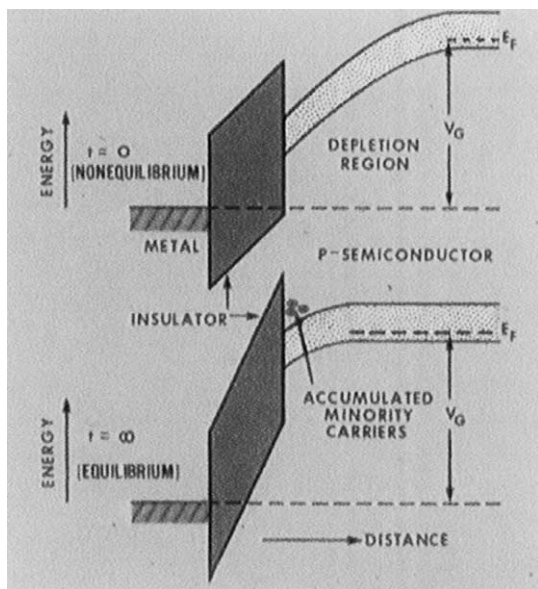


Fig. 3. A plot of electron energy versus distance through the MOS capacitor with a voltage applied showing the conditions with no charge and a full packet of charge.

came to mind was the MOS capacitor in depletion (Fig. 2). Charge can then be introduced into this depletion region with the amount of charge stored being the magnitude of the signal (Fig. 3).

The last problem was to shift the charge from one site to another, thereby allowing manipulation of the information. This is solved by simply placing the MOS capacitors very close together in order to pass the charge easily from one to the next by applying a more attractive voltage to the receiver (Fig. 4).

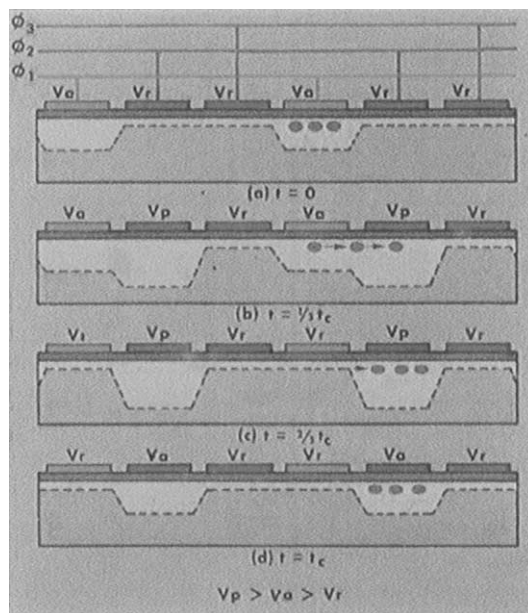


Fig. 4. The basic CCD structure showing MOS capacitors placed close together in a row and connected to a three-phase voltage source. The top figure shows the storage phase with  $V_a$  applied to one set of electrodes and a smaller rest voltage  $V_b$  applied to the other two. One site has charge which can be supplied by light incident on the structure and the other has no charge caused by the absence of light. The second figure shows the transfer phase where a larger voltage,  $V_p$ , is applied to the adjacent plates to transfer charge from one to the next. The last two show resetting the voltages to the initial state with the charge information shifted by one site. This is continued to an output device at the end of the row in order to read the stored information. Many other storage and transfer schemes are possible.

This completed the basic invention [1]. It should be stressed that the basic unit of information in the device was a discrete packet of isolated charge and not the voltages and currents of circuit-based devices. The CCD is indeed a functional device and not a collection of individual devices connected by wires.

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 and tested [2] (Fig. 5). The first device was very crude but charge transfer was successfully demonstrated and this was followed by the first integrated structure, which was an eight-bit

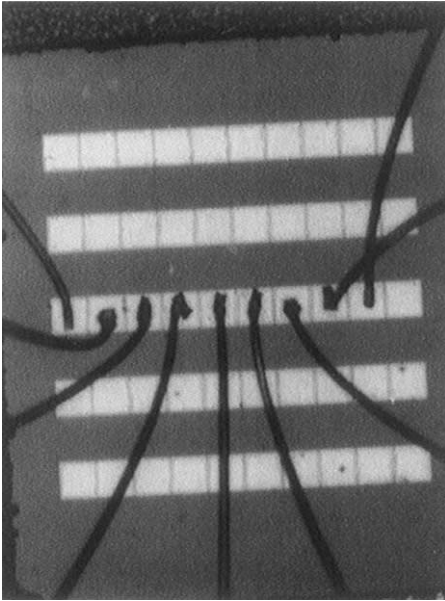


Fig. 5. The first CCD device. Charge was introduced in the first MOS capacitor by thermal generation and then transferred to the output where it was detected by pushing the charge into the substrate and measuring the substrate current.

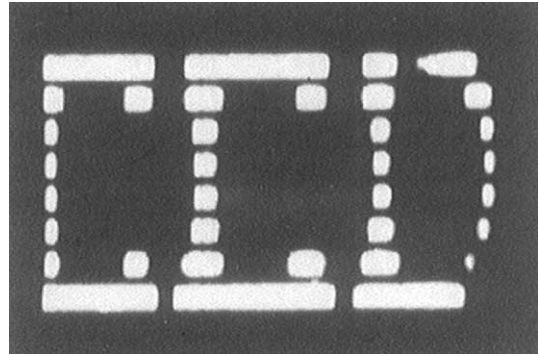


Fig. 7. The first use of a CCD as an imaging device. A display of the 8-bit structure used in the linear scanning mode.

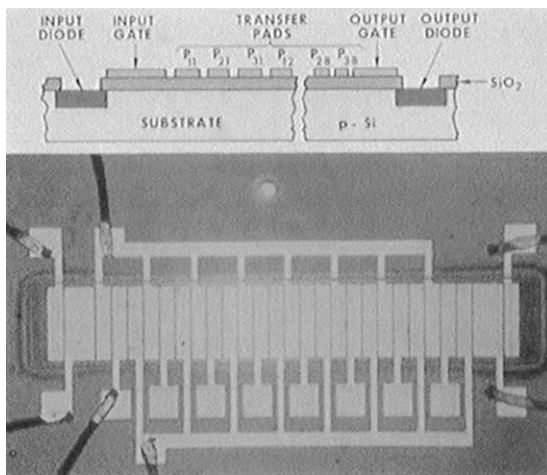


Fig. 6. The first integrated device with three-phase metalization and diffused input and output.

three-phase device (Fig. 6). This demonstrated shift register action with electrical inputs and outputs as well as demonstrating use as an imaging device (Fig. 7).

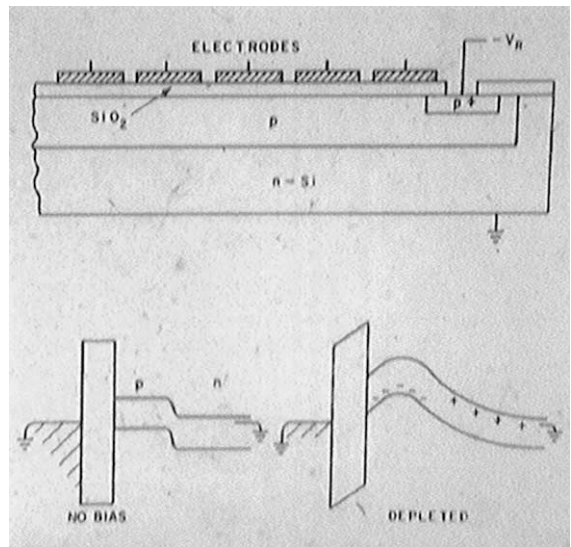


Fig. 8. The buried channel structure and a plot of electron energy vs. distance into the device. This is a p-channel device in which the holes float upwards and are contained in the potential well in the interior of the semiconductor.

There followed a behve of activity and invention by many coworkers including our own invention of the buried channel CCD. It had soon become apparent that a major limitation of the device was charge transfer inefficiency resulting from surface state trapping at the silicon-silicondioxide interface. This was a major source of signal degradation as the charge was transferred from one storage site to the next. So Bill and I again got together and in a single afternoon invented the buried channel CCD which placed the stored

charge in the interior of the semiconductor where there was relatively little trapping (Fig. 8).

A period of rapid development followed both at Bell Labs and other companies. One major activity was to make an area imaging device. Many different schemes were devised. One was the frame transfer geometry (Fig. 9), which was used to make a device with Picturephone resolution. This was put in a completely self-contained camera (Fig. 10) and feasibility was demonstrated. We also made linear imaging devices (Fig. 11) for use in scanning applications such as facsimile machines.

Since those early days, applications have blossomed in several major areas as the technology

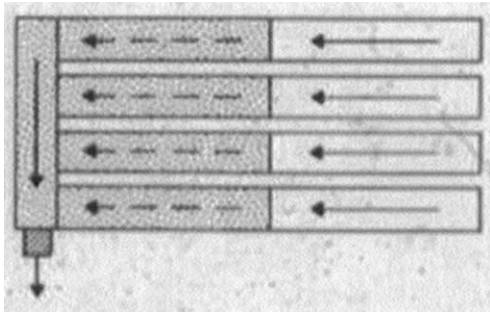


Fig. 9. The frame transfer structure made from rows of linear devices on a single chip. The light image is focused on the two-dimensional array on the right where charge proportional to the light intensity is stored in the elements. After a frame time, the charge is quickly shifted to the array on the left and read out line by line to the output diode during the next frame time.

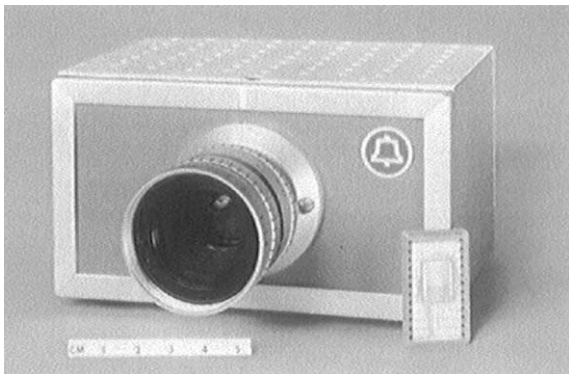


Fig. 10. A camera with all video circuitry contained in the box. The area imaging device shown had the 250 line resolution needed for the Picturephone application.

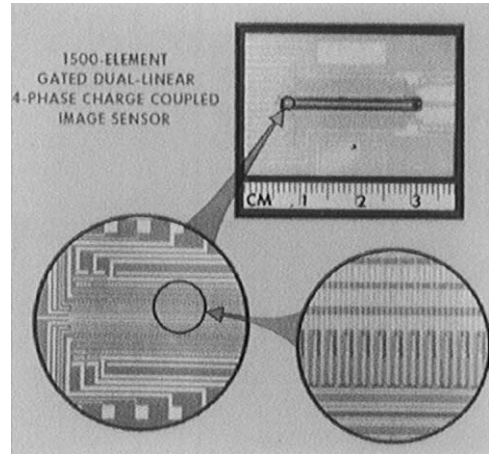


Fig. 11. A 4-phase, 1500-element linear imaging device.

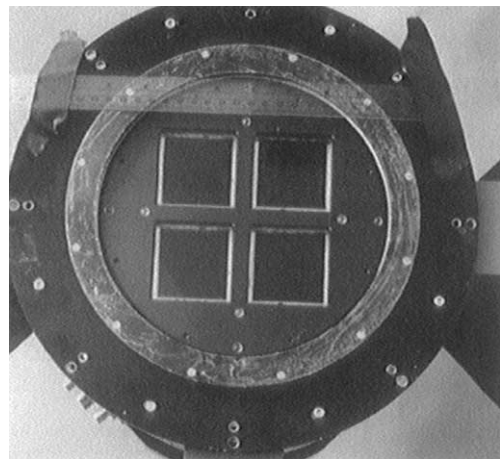


Fig. 12. Four 4-million-element CCDs mounted for astronomical observations.

improved and became more economically feasible. Camcorders are certainly prevalent and digital cameras are just now coming into wide-scale use. Imaging tube technology has been virtually eliminated from use in commercial TV by CCDs. Satellite surveillance uses the most up-to-date CCD technology for military, weather, and environmental applications. Numerous applications exist in medical, scientific, robotic and other fields. Individual and group video communication may eventually become common. Widespread use in astronomical applications has greatly expanded our knowledge of the universe. Large area devices



Fig. 13. A picture taken with a CCD mounted in the Hubble Space Telescope. It shows galaxies 3 billion light years away which had not been seen before.

have been used in telescopes in place of film to take advantage of their unique properties when the technology is pushed to its limits (Fig. 12). These include up to 90% quantum efficiency, (the best photographic film is 5%); long integration times since at 160 K, dark current is 20 electrons/pixel/h and pixels contain  $>10^5$  electrons; low transfer inefficiency, down to  $10^{-6}$ ; and broad spectral range using special structures. This can be seen by comparing a CCD image (Fig. 13) with one taken with photographic film (Fig. 14).

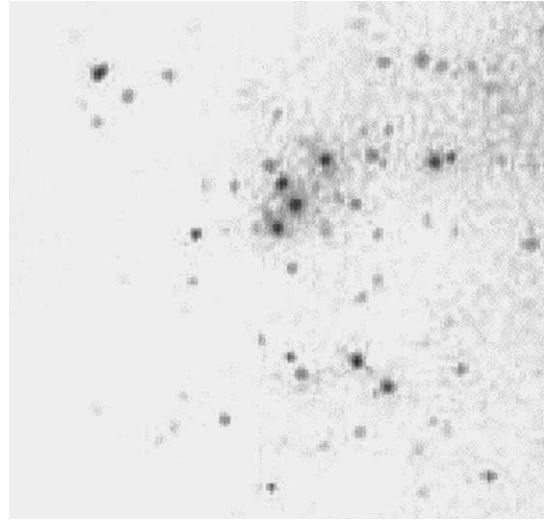


Fig. 14. The best photographic film image taken of the same area.

In summary, CCDs were born in the Si–SiO<sub>2</sub> revolution and created their own revolution in widespread imaging device applications because of their unique properties.

## References

- [1] W.S. Boyle, G.E. Smith, *Bell System Tech. J.* 49 (4) (1970) 587.
- [2] G.F. Amelio, M.F. Tompsett, G.E. Smith, *Bell System Tech. J.* 49 (4) (1970) 593.