A state-of-the-art report on charge-coupled devices and scanned photodiode arrays.

Solid-State Image Sensors— TV Camera Tube Successor?

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AN EXPERIMENTAL TV camera has been developed that is no larger than a pack of cigarettes. Equipment is being installed at supermarket checkout counters that can automatically read price tags. There is even a machine that enables blind people to read ordinary printed material. All of these developments are made possible by the use of solid-state image sensors—a special type of integrated circuit.

An image sensor can contain hundreds, even thousands, of individual photosensitive elements on a single chip of silicon. It is normally mounted in a standard IC package that is covered with a transparent top. When a scene strikes the image sensor, usually through a lens as shown in Fig. 1, the individual elements of the sensor can be scanned electronically and their outputs displayed.

Area vs. Image Array. The photosensitive elements of an image sensor can be in either a linear or an area array. In a linear array the elements are in a single line; in an area array, they are in a two-dimensional matrix.

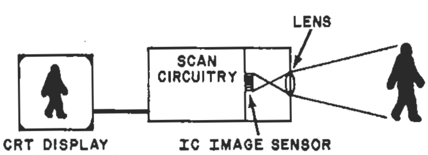

Fig. 1. An image-sensor system.

A linear array can be used to produce a two-dimensional picture, but only one line at a time as the image moves across the sensor. The number of elements in an array determines the resolution of the picture. The effect of resolution on picture quality is shown in Fig. 2. Here, the same picture is scanned by five different linear arrays. The array with the lowest resolution (32 elements) produced the picture at the right, while the picture on the left was produced by an array with 512

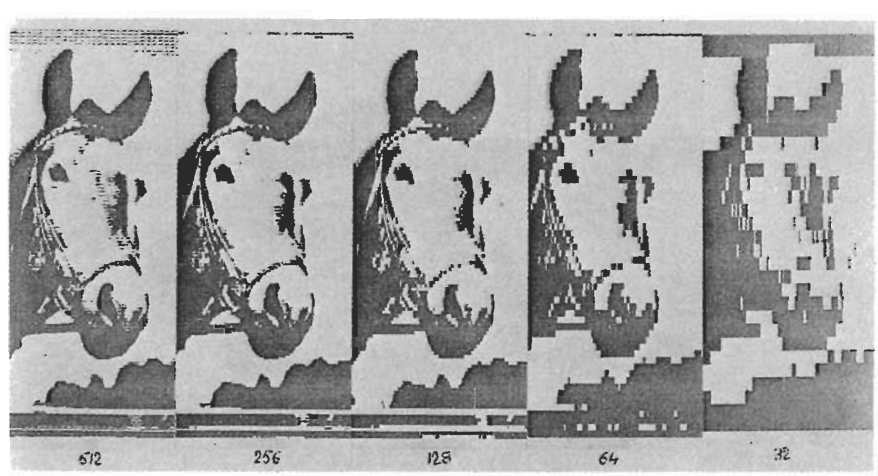

Fig. 2. Photos of displays show how resolution affects picture quality. Number of elements in array increases from right to left.

elements. The improvement in quality from right to left is obvious.

The advantage of an area array over a linear array is that the image doesn't have to be scanned from top to bottom to produce a two-dimensional picture An example of an imaging system using a lens to image a picture onto a 2500-element area array is shown in Fig. 3. The sensor is electronically scanned and its video output is displayed on a CRT. The array used is a Reticon Model RA50X50 (Fig. 4).

The reading aid shown in Fig. 5 was developed at Stanford University and has a 144-element (6 X 24) image sensor. A small camera containing the image sensor is used to scan a printed page. The outputs of the sensor control a 144-element tactile display that a blind person can feel by fingertip. This reading aid, known as the Optacon (Optical to Tactile Converter) is being produced by Telesensory Systems Inc.

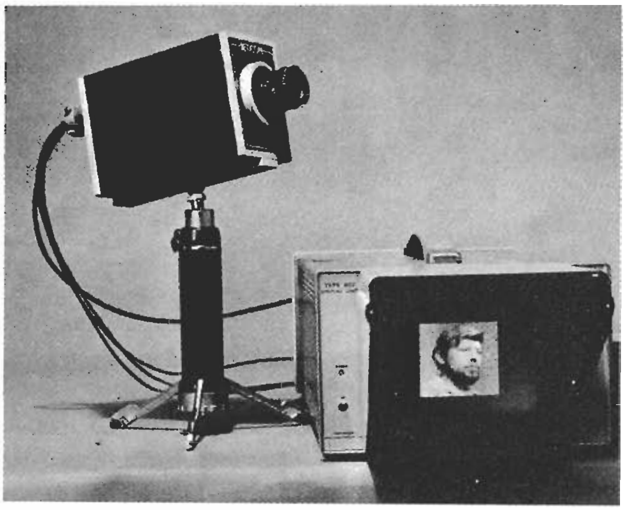

Fig. 3. Solid-state imaging system using a 50 by 50 sensor array. The image can be seen on CRT in front.

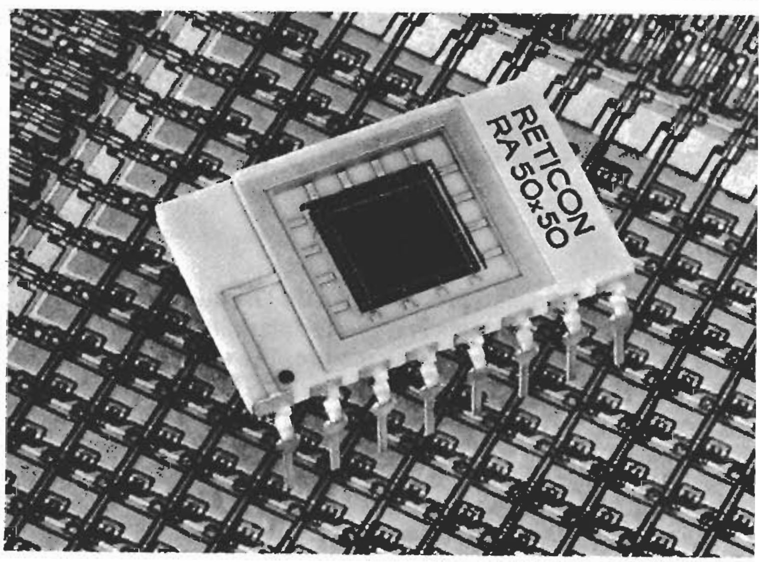

Fig. 4. Close-up of the Reticon RA 50×50 sensor. The background is photo of the array magnified many times.

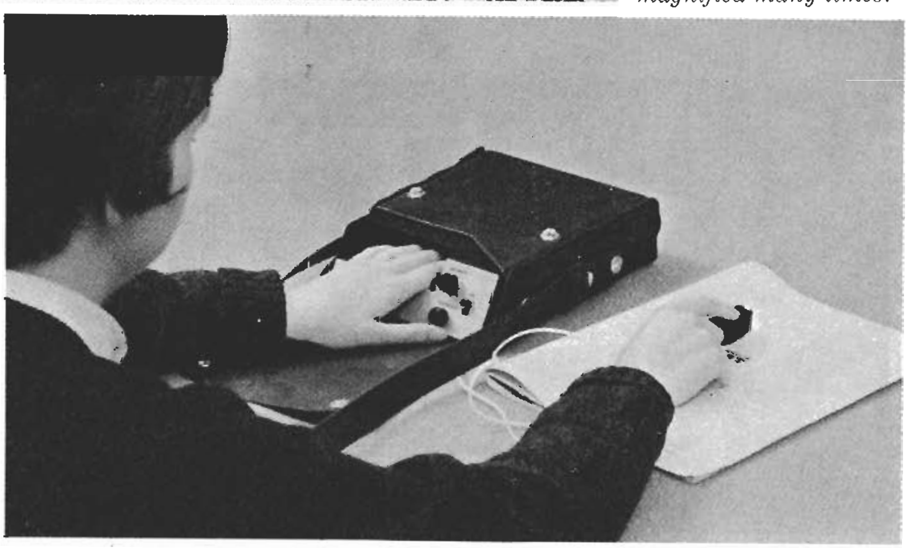

Fig. 5. Reading aid for blind is used by scanning letters with sensor in right hand and feeling them with left hand on tactile display.

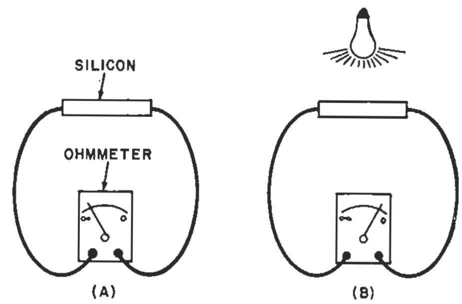

Fig. 6 With normal light on piece of silicon (A), resistance is high. More light lowers resistance (B).

Types of Image Sensors. Integrated circuit image sensors can be built in a number of different ways. The two most common types are the charge-coupled device (CCD) and the MOS scanned photodiode array. Both types make use of the inherent light sensitivity of silicon.

The light sensitivity of silicon can be observed by performing the simple experiment shown in Fig. 6. When a strong light is shining on the silicon device, the resistance of the silicon is seen to decrease. What is being observed is the process of *photogeneration*. When light interacts with silicon, current carriers (both holes and electrons) are generated, reducing the resistance. In fact, each photon that interacts produces one hole and one electron (sometimes called a hole-electron pair).

Silicon is not uniformly sensitive to all wavelengths of light. In fact, silicon image sensors are generally much more sensitive to red light and the

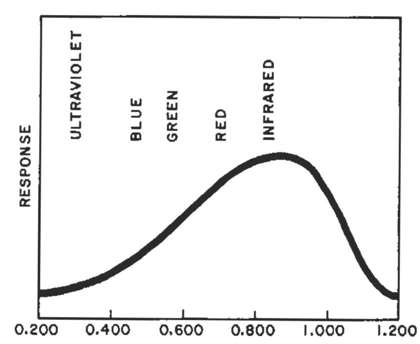

Fig. 7 Spectral response of silicon to various colors of light.

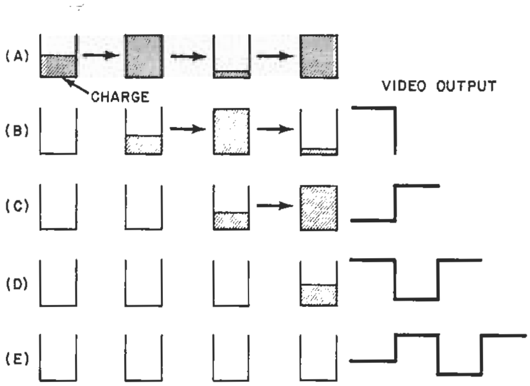

Fig. 8. Charges in CCD array are transferred from left to right to produce a video output.

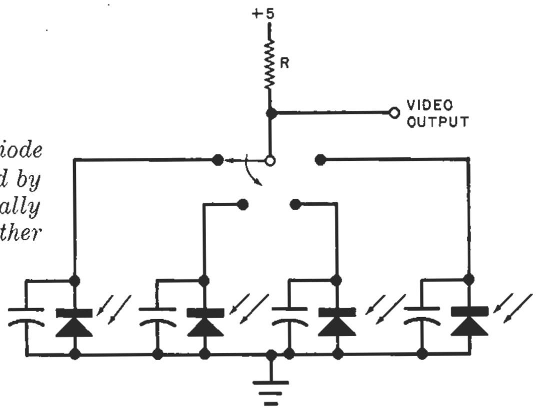

Fig. 9. Photodiode array is scanned by switching sequentially from one to another

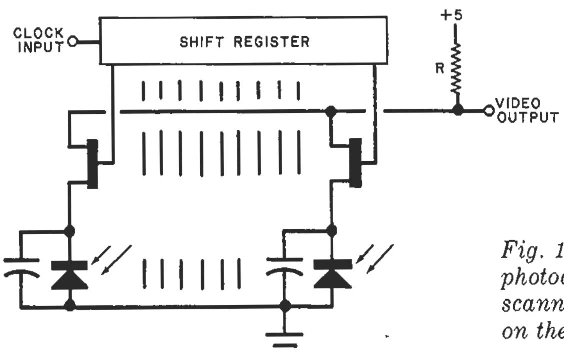

Fig. 10. Self-scanned photodiode array is scanned by transistors on the IC chip.

near infrared than they are to shorter-wavelength blue light. The sensitivity of an image sensor to different colors is summarized in the spectral response curve shown in Fig. 7.

CCD Arrays. Charge-coupled device image sensors enjoy one major advantage over MOS scanned photodiode arrays: they can be built more densely and with larger numbers of elements. The basic photosensitive element in a CCD is an MOS capacitor. An entire array of these capacitors makes up the CCD image sensor. The key feature of the CCD is that charges can be transferred sideways, from one MOS capacitor to another.

The operation of the CCD image sensor is shown diagrammatically in Fig. 8. Each of the capacitors can be considered as a small "bucket" that holds a charge. When light shines on the sensor, a charge is produced in the bucket through photogeneration. The more light that shines on a particular bucket, the more charge produced. The video information is read out by quickly transferring the charge from one bucket to the other and measuring the charge at the output. All of the charges are emptied from the buckets in this process and the cycle can then be repeated.

The image sensor with the largest array that is commercially available today is a 100 X 100 (10,000-element) CCD array produced by Fairchild Semiconductor. This image sensor produces excellent pictures, but falls short of providing full television resolution. Before that can be achieved with an IC, a 512 X 320 (163,840-element) image sensor must be developed. This would be a very large sensor indeed, and its development presents a real challenge to the electronics industry. RCA has recently announced an experimental CCD that comes close to providing this resolution, but it is not being produced commercially at this time.

Scanned Photodiode Arrays. In the MOS photodiode image sensor, the photosensitive element is a silicon diode. When reverse-biased and in the dark, a very small leakage current flows through a photodiode. This is called "dark current." When light shines on the diode, current carriers are generated and more current flows; and the current increases as the light intensity is increased.

The operation of a scanned photodiode array is shown in Fig. 9. The four diodes are sequentially scanned by a rotating switch. Notice that a small capacitor is shown across each diode. The capacitors are not separate components; they represent the inherent capacitances of the diodes. When a diode is selected by the switch, its inherent capacitor charges up through the resistor to the level of the 5-volt supply. As the switch moves on to another diode, the first capacitor discharges through its photodiode. If no light is hitting the diode, the small dark current will only partially discharge the capacitor. With more light on the diode, the capacitor is more fully discharged by the higher current. Now, when that diode is again selected by the switch, an output signal is produced as the capacitor recharges to 5 volts. This video output signal is caused by the voltage drop across the resistor. The more the capacitor is discharged, the greater will be the video signal. Image sensors that operate in this manner are operating in the charge-storage mode.

Scanned photodiode sensors use MOS transistors as switches to scan the diode array. The photodiodes are actually the source-to-substrate diodes of the MOS transistors. As shown in Fig. 10, the MOS transistors are sequentially "closed" by pulses from a shift register which is indexed by a clock input. Image sensors that include shift register circuitry right on the IC are said to be self-scanned. The Reticon image sensor mentioned earlier is an example of a self-scanned MOS photodiode array. ◈