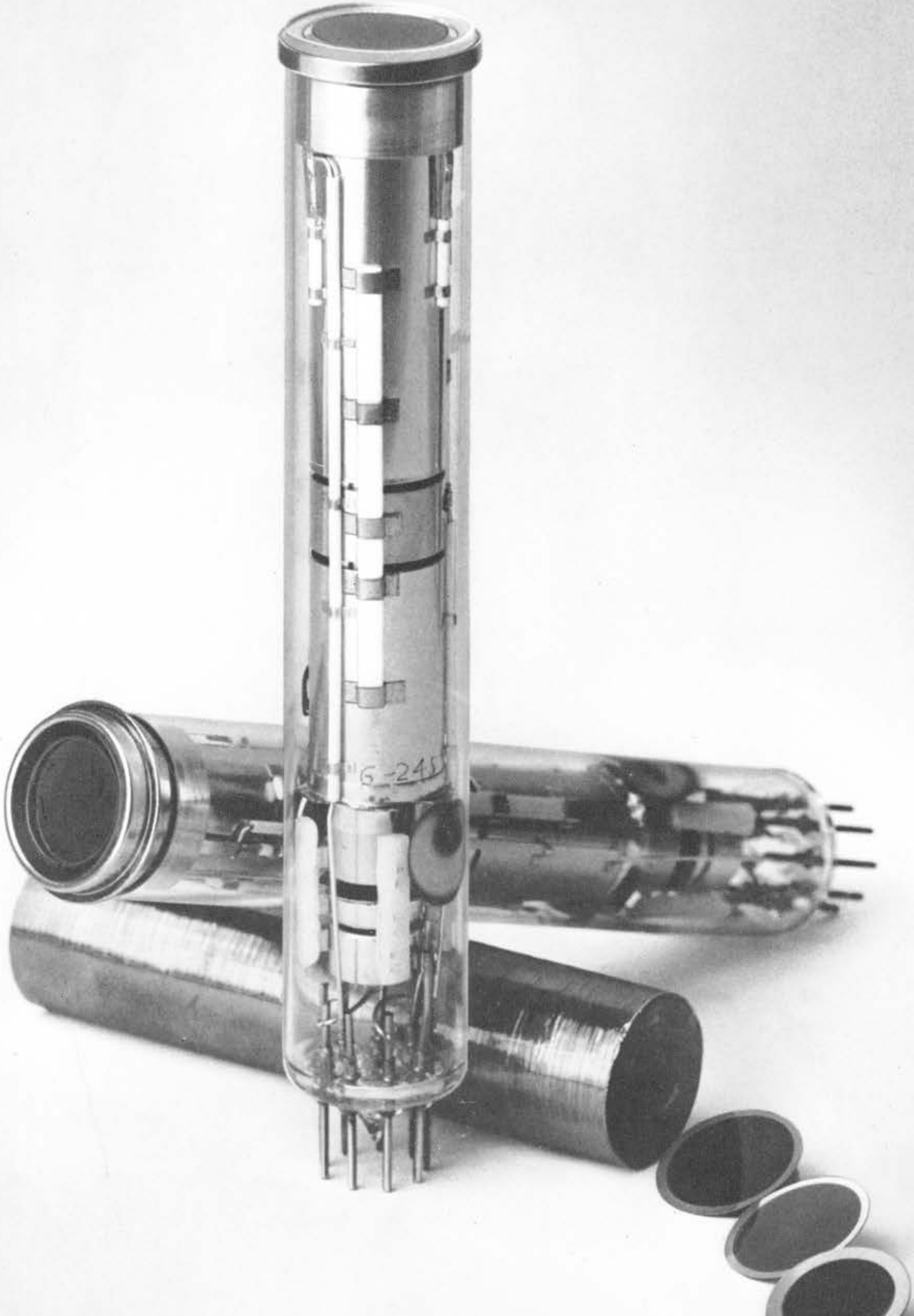

A new camera tube for the PICTUREPHONE set uses an integrated silicon photo-diode array combined with conventional electron beam scanning. The result is a vidicon-type of camera tube which is far more sensitive and reliable than any now being used.

A "Solid-State" Electron Tube For the PICTUREPHONE Set

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A NEW CAMERA TUBE for the PICTUREPHONE® visual telephone combines some of the best features of the "old" and the "new" arts of electron device design. From electron tube technology it takes the low cost and simplicity of electron beam scanning; from integrated circuit technology, the reliability and sensitivity of a silicon photodiode array. The result is a camera that will operate reliably over an extremely wide range of light levels including exposure to direct sunlight.

Of various camera tubes in use, the small, simple, potentially low cost vidicon is most suitable for PICTUREPHONE service. It is used, in fact, in the experimental version of the PICTUREPHONE station set. Unfortunately, the vidicon is susceptible to several phenomena, collectively called "burn-in," which lower its reliability and preclude electronic control of the camera's field of view.

To understand the deficiencies of the vidicon in the PICTUREPHONE application and how these are overcome in the new camera tube, it is appropriate to begin by describing the operation of the vidicon. A conventional lens forms an image on a photoconducting target which performs the image sensing function. Scanning is accomplished by an electron beam which is focused and deflected in a manner similar to that used in television picture tubes, except that the scanned area is a half-inch square (see the drawing at the top of page 176).

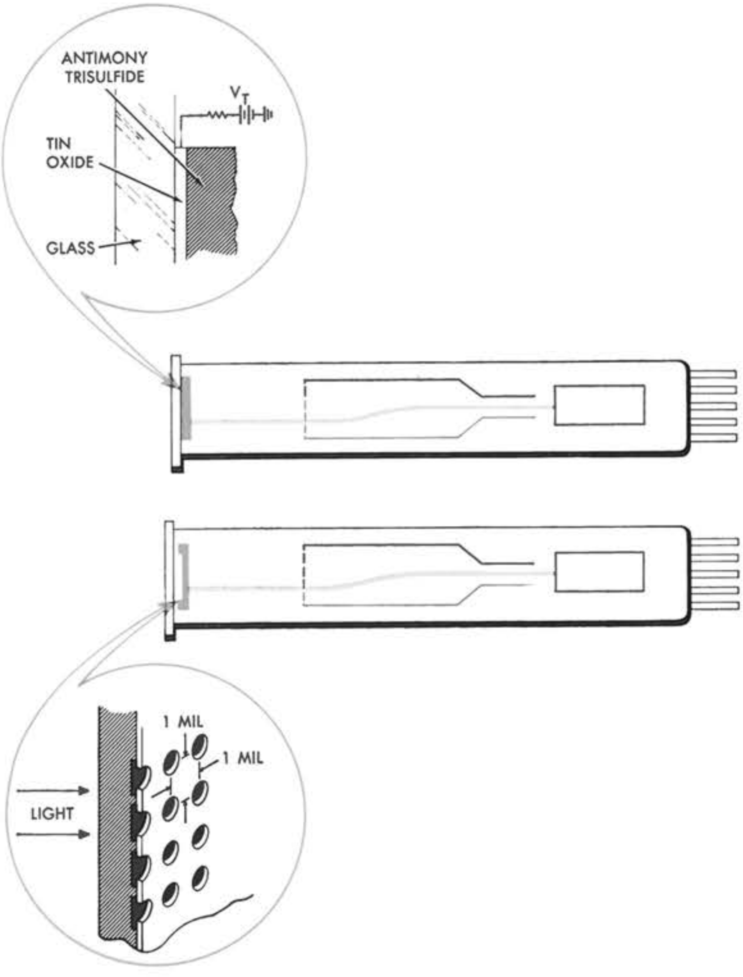
The electron beam scans the target along a pattern of lines called a raster. (See the drawing on page 176.) A complete scan of a raster takes one-thirtieth of a second, a period known as a frame interval. The scanning operation generates a video signal which is proportional to the image intensity at the position of the scanning beam.

In the vidicon, the target consists of a glass substrate which is usually the tube window, a transparent conducting tin oxide film and a photoconducting film less than 0.0001 inch thick. Antimony tri-sulfide is one of the commonly used photoconducting film materials. In the dark the film is a fairly good insulator; when exposed to light, it is a conductor.

In operation the conducting tin oxide layer is held several tens of volts positive with respect to the electron beam cathode. The landing energy of the beam electrons is sufficiently low that fewer electrons than are incident leave the surface by secondary emission. In the area of electron impact (or site) the surface of the film accumulates a negative electronic charge until its potential approximates that of the cathode and additional electrons are prevented from landing. The area of a site, about 0.001 inch in diameter, corresponds to the beam diameter and approximates the smallest resolvable picture element.

It is convenient to consider that each site behaves like a small capacitor. One plate of this capacitor is the conducting tin oxide film opposite the site. The other plate is the surface of the photoconducting film. Since the potential of this surface is established at cathode (ground) po-

A vidicon camera tube (foreground) and the new camera tube for the PICTUREPHONE set. The main change is in the target structure—the round wafer fabricated from the bar of bulk silicon—which contains an array of about 300,000 photodiodes.



The conventional vidicon (top) and the new camera tube have basically the same physical structure. The difference is the photoconducting target. The target of the vidicon is an evaporated film of antimony trisulfide (or a similar material) about one ten-thousandth of an inch thick which is supported by the face plate of the tube. The target of the new tube is a self-supported silicon wafer about the diameter of a nickel and about eight ten-thousandths of an inch thick in the area of light sensitivity. This area contains an array of about 300,000 diodes formed on the wafer by integrated circuit techniques.

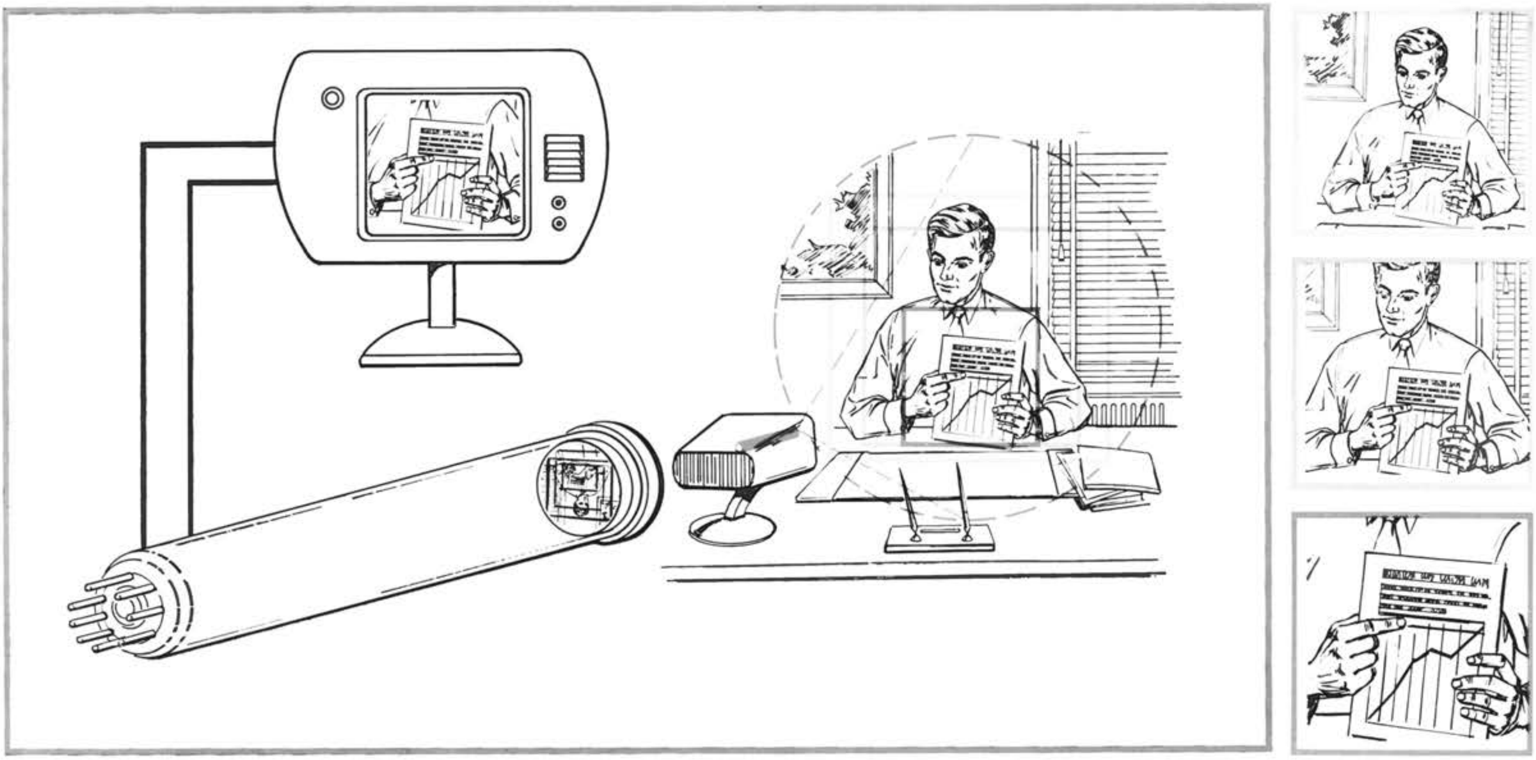
tential by the electron beam, the voltage across the film site capacitor equals the voltage applied to the tin oxide film. In the dark this voltage can be maintained for many seconds since the film is a good insulator.

Light enhances the leakage current through the film, causing the film site capacitor to discharge between successive scans of the site by the electron beam. Reduction of the capacitor voltage by the discharge process increases the surface potential since the potential of the tin oxide film is held virtually constant. The degree of discharge, and hence the increase in surface potential, depends on the intensity of the light at the site position. Thus, the surface potential of the photoconducting film exhibits variations corresponding to intensity variations in the image. Since the capacity of the surface relative to ground is negligibly small, discharge of the film site capacitor produces no current in the external circuit containing the target resistor.

When the scanning beam returns to a given site it quickly replaces all the negative charge dissipated by leakage in the preceding frame interval, thus returning the site to cathode potential. The replacement charge repels an equivalent negative charge from the film-tin oxide interface which flows back to the cathode through the target resistor and ground. Voltage variations produced across the target resistor in this way represent light variations and are uniquely related to the instantaneous position of the scanning spot. This constitutes the video signal.

To sum up the process: the scanning beam sequentially makes electrical connection to each target site capacitor bringing the surface plate almost instantly to ground potential, and recharging the capacitor. The associated charging current constitutes the video signal. As the beam goes on to access all the other sites, the capacitor slowly discharges under the action of the incident light, however, producing no current in the external circuit. The process is repeated and the capacitor is recharged when the beam returns to the site. In general, the resulting video signal

Formation of the conventional interlaced raster. Circular boundary of the illustration encloses the image the camera lens forms on the target of the tube. The rectangular area of horizontal lines —the raster—defines the transmitted image. Each field of the raster (blue lines are the first field, black lines the second) is scanned in a sixtieth of a second, the two scannings comprising a frame. Frame rate of 30 per second assures normal animation in the displayed picture. Field rate of 60 per second precludes broad area flicker.



The new camera tube electronically controls the field of view of the displayed image by changing the size and position of the scanned area on the target. The camera lens produces a fixed-size image. The displayed image is defined by the raster which can be varied by varying the beam accelerating voltage or bias current in the deflection coils. At the display unit, the synchronizing information controls only the time of the raster sweeps, not the length or spacing of the lines. Changing the raster size varies the magnification of the scene. Wide angle, normal, and telephoto fields of view are shown at right side.

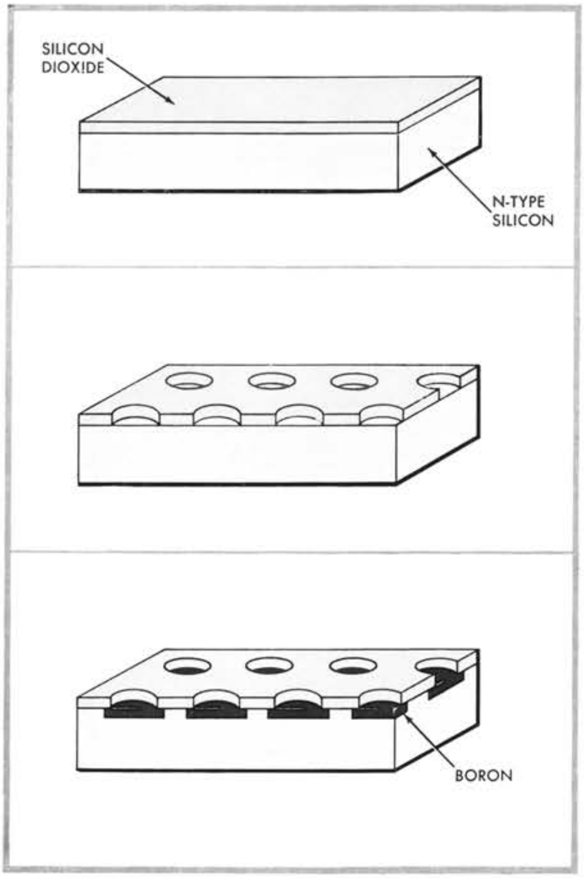
does not increase linearly as the intensity of the light increases, but rather more slowly. For example, doubling the intensity of the light increases the video signal by a factor of 1.5. The lack of linearity is related to the manner in which photocurrent is excited in a highly insulting film.

Under normal conditions only a small part of the video signal results from leakage current not produced by the light. Commonly called the dark current of the target, this can degrade the displayed picture if it is not uniform over the target area or if it is too large and discharges the film voltage too rapidly. In the latter case light sensitivity is reduced since the electric field within the film is reduced. Also, charge may spread laterally from one site to the next impairing the resolution.

The burn-in phenomenon, which impairs the usefulness of the vidicon for the PICTUREPHONE camera, is associated with damage to the photoconducting film caused by high light levels or electron beam bombardment. If the camera "stares" at an electric light for any length of time, damage to the film may accumulate. The damage shows up as local variations in the dark leakage current and light sensitivity. The viewer sees ghost images in the picture. If the light is from a photographer's flash gun, for instance, burn-in may be instantaneous, completely destroying the usefulness of the tube.

The scanning beam may cause a similar type of damage called raster burn-in. Light sensitivity and dark current differ considerably from the normally scanned to previously unscanned areas of the raster. Therefore, if the size of the raster is increased or its position is changed, the edges of the previous raster are clearly visible in the displayed picture. If it were not for raster burn-in, zooming and centering—which can be accomplished by changing the size and position of the raster to permit transmission of only part of the image formed by the lens—could be done merely by changing voltages associated with the beam focusing and deflection structure. (See the drawing above.)

Burn-in damage in the vidicon arises from the intrinsic properties of the photoconducting target film. The film requires extremely low conductivity in the dark and good photoconductive response to visible light. All known materials suitable for the vidicon and satisfying these requirements are subject to burn-in. Although the precise nature of the damage is not understoood it is asso-



Major processing steps (sequentially top to bottom) in the fabrication of the diode array. It starts as a silicon wafer several thousandths of an inch thick. An oxide layer about 25 millionths of an inch thick is then grown on the surface of the silicon. Photo-lithographic techniques are used to generate an array of holes in the oxide. Boron is diffused into the silicon through the holes forming the p-type islands. In this step the remaining oxide serves as a diffusion mask.

ciated with the fact that these are compound semiconductors in an amorphous state.

Reverse biased silicon diodes have been used as photodetectors and show good sensitivity while being completely free from burn-in. Attempts have been made to construct arrays of such diodes to function as video image-sensing devices. To date these have required extremely complex access circuitry and have posed economic and technological problems which are as yet unsolved.

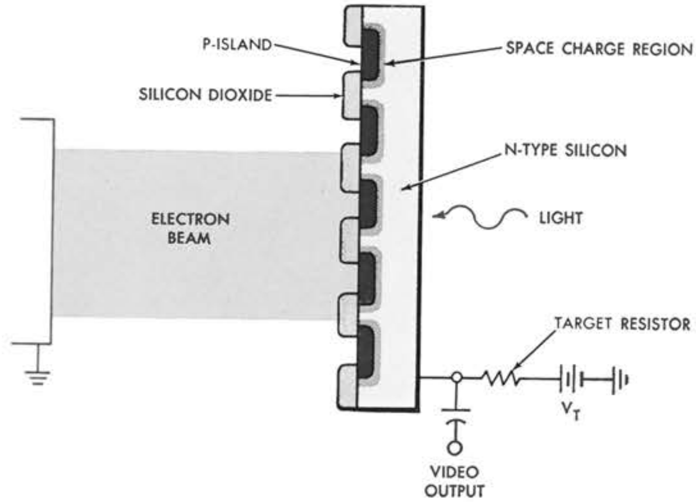
The design of the new camera tube for the PICTUREPHONE station set retains the best elements of the vidicon while incorporating the advantages of the array of silicon photodiodes. The electron beam scanning structure is identical to that of the vidicon. (See the drawing on page 176.) Its target structure, however, is an array of reverse-biased diodes on a silicon wafer about the size of a nickel. A typical array, fabricated using integrated circuit techniques (see the drawing above), contains close to 300,000 individual diodes in an area about one-half inch square. The extreme simplicity of the array allows fabrication of exceptionally uniform diodes with virtually no defects.

The photodiodes face the electron beam. (See the drawing on page 179.) During operation, the electron beam charges the surface of the silicon to cathode potential, reverse biasing the diodes. The n type substrate maintains a uniform potential (equivalent to the conductive tin-oxide layer in the vidicon) except for a space charge region surrounding each diode. Leakage current per diode is sufficiently small (less than 10^{-11} amperes) that reverse-bias voltage can be maintained for many seconds in the dark. Since the scanning beam is larger than the diode spacing, the discrete nature of the array does not significantly limit the resolution of the tube, and registration of the beam with the rows of diodes in the array is unnecessary. In many respects a diode is analogous to the target site capacitor of the vidicon.

An image is formed on the surface of the target opposite to the array. The incident light penetrates the silicon substrate and is absorbed, creating hole-electron pairs. Holes are minority carriers in the n type material of the substrate. A fraction of them diffuse into the space charge region where the space charge field immediately sweeps them across the junction into the p type region or island, thus discharging the photodiodes. This process occurs during the thirtieth of a second between successive scans of the beam. The video signal is created as the scanning electron beam recharges successive diodes along the scanning path. The signal is directly proportional to the number of holes discharging the diode which, in turn, is directly proportional to the light intensity.

A number of the holes created in the n type region recombine there with electrons and are lost. This reduces what is called the collection efficiency—the number of holes reaching the space charge region per incident photon—and has a direct bearing on the sensitivity of the camera. The greater the collection efficiency, the greater the sensitivity.

Controlling the collection efficiency is a matter of controlling the bulk minority carrier lifetime and the surface recombination velocity which characterize the recombination process. Long lifetimes and low recombination velocities increase efficiency. Moreover, if virtually all the incident light is absorbed in the substrate and if the carrier lifetime, and the surface recombination



Geometry of the new camera tube. The silicon substrate is held at a potential of about 10 volts relative to the electron beam cathode. As the beam scans the diode array, it charges the p-type silicon islands down to cathode potential, leaving the diodes in a reverse-bias condition. A space charge region forms around each island, serving as the collection area for photo excited holes generated in the substrate. The holes are swept across the space charge region partially discharging the diodes. At the next scanning the diodes are recharged, the islands returning to cathode potential. Recharging current flows through the target resistor back to the cathode, creating a video output signal, which is felt across the condenser.

velocity are fixed, collection efficiency increases as the target is made thinner. As the holes diffuse toward the diode space charge region, they also diffuse laterally reducing the target resolution. The thinner the target, the greater the resolution. The target of the new tube is made as thin as possible—about 0.0005 to 0.0008-inch thick—in the sensitive region. The thicker outer rim provides structural strength. Increasing the target voltage, which increases the reverse-bias voltage, increases the width of the space charge region of each diode. This also increases the sensitivity and resolution. However, the diode leakage current also increases with increase in reverse-bias voltage and only a limited degree of improvement can be achieved in this manner.

Collection efficiency is greater for infrared than for visible light since short wavelength photons are absorbed closer to the surface of the silicon substrate away from the diodes. Visible light (0.4 to 0.7 microns) is absorbed within about 0.0001-inch of the surface. Near-infrared light penetrates somewhat further. Holes created deeper in the substrate by near infrared wavelength light have a smaller probability of recombining with electrons before reaching the space charge region. For wavelengths of light greater than about 1.1 microns the target is virtually transparent and the collection efficiency is extremely low.

Early versions of the new tube were markedly more sensitive in the near-infrared than in the visible part of the spectrum. However, improved fabrication techniques have increased the minority carrier lifetimes and decreased the surface recombination velocities. Collection efficiency in recent models of the tube exceeds 40 per cent over wavelengths of 0.4 to 1 micron and it is believed that further improvement is possible. The spectral response is much broader and flatter than that of the vidicon. As a result, it is possible to tailor the spectral response to a specific requirement by the use of suitable filters. For example, if it is desirable to match the spectral response of the eye, a filter approximating this response can be inserted in front of the tube window. In the PICTUREPHONE set application it is necessary to eliminate the infrared response above 0.8 microns since the relative gray scale balance of most scenes is distorted when viewed in infrared light.

In contrast to the vidicon the signal output is directly proportional to the incident light intensity. For these reasons a direct comparison of sensitivity is not possible. However, under normal operating conditions for the PICTUREPHONE camera the new camera tube requires only about one fifth the illumination level required for the vidicon. Also, the dark current is several times less than that of the vidicon.

In the vidicon the photocurrent lasts for several frame times, producing image persistence or lag. Lag is elminated in the new tube because the minority carriers diffuse out of the silicon substrate within a few microseconds—about one ten thousandth of a frame time.

Exploiting the properties of silicon in the new camera tube, has led to other advantages over the vidicon. First, the high thermal conductivity and chemical stability of silicon liberates the new tube from any possibility of burn-in. This leads to the wide range of light levels under which the tube can operate and permits electronically controlled zooming and centering. Second, in contrast to the antimony tri-sulfide used for the photoconducting film of the vidicon, silicon can be baked at high temperatures. Thus contaminating substances can be eliminated from the tube during vacuum processing without damaging the target structure. This increases the life and reliability of the cathode.

The final result is a vidicon-type of camera tube far more sensitive than any now being used and with a potential lifetime several times greater than that of its conventional predecessors.