11.1 PHOTOSENSITIVITY

A photosensitive camera tube is the light-sensitive device utilized in a television camera to develop the video signal. The image of the scene being televised is focused upon the light-sensitive member of this tube.

The energy present in the photons of light generates free electrons. In the case of a photoemitting light-sensitive surface, they are emitted from the surface into the vacuum of the tube. When a photoconducting material is used, the electrons are freed in the bulk of the material to carry current through it.

The function of the camera tube is to interrogate the electron charges that are developed in this process at successive points of the optical image, in synchronism with the television raster scan.

11.1.1 PHOTOEMITTERS. Photoemitters are alloys of metals (usually the alkali metals) that form a semiconductor. They have both a low band gap and a low electron affinity. The sum of the band gap and the electron affinity is sometimes called the *work function,* i.e., the minimum amount of energy that an electron from the material must receive to cause it to be emitted from the surface of the material into a vacuum. (See Fig. 11-1.) The energy involved is expressed in electronvolts. In metals there are many free electrons, and so energy from the photon does not have to be expended to free electrons from valance states to conduction states; i.e., the band gap is negligible. (See Fig. 11-2.)

The energy for photoemission of an electron must come from the energy of a single photon of light. (The probability that any electron will receive energy from two photons is extremely small.) The energy of photons of visible light ranges from 3.11 to 1.77 eV, corresponding to wavelengths of 400 and 700 nm, respectively, the limits of perception of visible light by the average person.

The energy of light in a photon of any wavelength is expressed as

$$E = h\nu \tag{11-1}$$

where h = Planck's constant (6.625×10^{-34} J-s)
ν = frequency of radiation, Hz
E = energy, J

and
$$\nu = \frac{c}{\lambda}$$

where c = velocity of light, 3.0×10^8 m/s, and λ = wavelength in meters

or
$$E = h\frac{c}{\lambda}$$

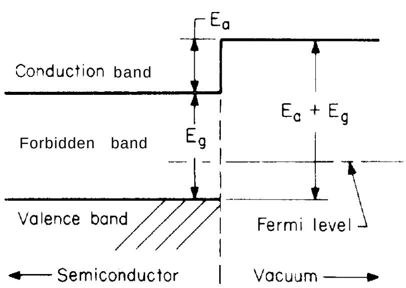

FIG. 11-1 Simplified semiconductor energy-band model (E_a, electron affinity; E_g, band gap). *(RCA Corp.)*

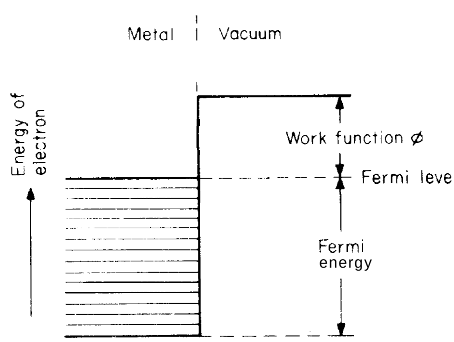

FIG. 11-2 Energy model for a metal showing the relationship of the work function and the Fermi level. *(RCA Corp.)*

For a wavelength of 700 nm (700×10^{-9}) (the red threshold of visible light)

$$E = \frac{(6.625 \times 10^{-34})(3 \times 10^{8})}{700 \times 10^{-9}} = 2.840 \times 10^{-19}\ \text{J} \tag{11-2}$$

Expressed in electronvolts

$$E = \frac{\text{J}}{\text{J/eV}}$$

where J/eV $= 1.602 \times 10^{-19}$, which gives

$$E = \frac{2.840 \times 10^{-19}}{1.602 \times 10^{-19}} = 1.773\ \text{eV} \tag{11-3}$$

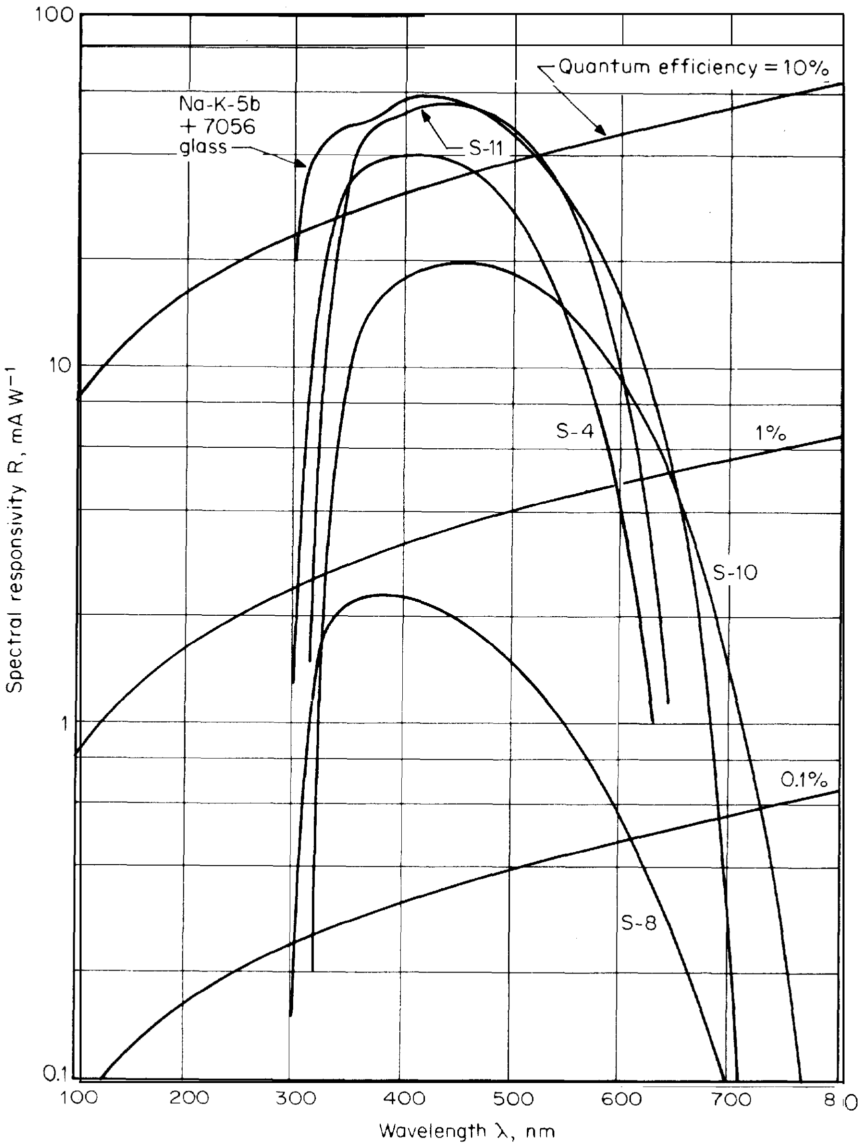

FIG. 11-3 Visible photoemitter characteristics. Absolute spectral responsivity of various photocathodes useful for the detection of visible light. *(RCA Corp.)*

An electronvolt is the energy of one electron when it has been accelerated through an electric field of 1 V.

When a photon of light is absorbed in a photoemitter, its energy is transferred to an electron in the valance band. This energy allows the electron to be liberated from the valance band, and it enters the conduction band. If it still has enough energy to overcome the electron affinity barrier, it may be liberated or expelled into the vacuum, and it becomes a photoelectron. The efficiency of the best photoemitters is about 0.3 or 30 percent. This refers to the average number of electrons emitted per photon of incident light at the wavelength of maximum photosensitivity.

Photoemitters are generally composed of complex alloys of the various metals, particularly the alkali metals or their oxides. These materials include various combinations of sodium, potassium, cesium lithium, rubidium, antimony, and silver.

In general, photoemitters have reasonably good electrical conductivity. If an electrical connection is made to the photoemitting material, it can supply large quantities of emitted electrons in response to large input fluxes of photons. The spectral and efficiency characteristics of photoemitters useful in television camera tubes are shown in Fig. 11-3.

11.1.2 PHOTOCONDUCTORS. Photoconductors are semiconducting materials designed to absorb light and utilize the energy of photons to raise electrons from the valance band to the conduction band. Thus they serve as charge carriers to increase electrical conduction through the material.

This is in contrast to the photoemitters, where the electrons are emitted from the surface of the material into a vacuum. Instead here the photons of light absorbed in a photoconductor serve to change the electrical conductivity of the material. The semiconductor band structure of a photoconductor can be represented almost exactly as the photoemitter. (See Fig. 11-l.)

The energy of the incident photon that is absorbed by the electrons in the valence band of the photoconductor need only be enough to allow the electron to overcome the band-gap barrier and enter the conduction band. These free electrons contribute electrical conductivity to an otherwise high-resistance material.

Photoconductors for camera tubes usually have very -high dark resistance. Specific resistivity is in the order of $10^{12}\ \Omega \cdot \mathrm{cm}$. Low-resistance photoconductors can be used if the material is formed into special structures. For detailed descriptions of photoconductors utilized in camera tubes and their relative performance characteristics see Sec. 11.7.

11.2 PHOTOELECTRIC-INDUCED TELEVISION SIGNAL GENERATION

Any practical camera tube designed for operation in a camera that must operate in normally available light levels is of the storage type. This means that the light from each point on a scene generates an electrical charge corresponding to the brightness of that portion of the scene. The device integrates and stores that charge in a two-dimensional array during the interval between successive scans of that portion of the scene. This greatly increases the effective sensitivity. If this storage did not occur, all the potential information developed during the interval between successive scans would not be utilized and therefore lost.

The function, then, of the photosensitive portion of the camera tube is to absorb photons of light. Next the device must generate, integrate, and store a two-dimensional pattern of charges. This stored pattern is then interrogated to develop a television signal whose waveform corresponds in amplitude to the scene brightness at each point in succession as the television scanning process proceeds.

11.2.1 PHOTOEMISSION-INDUCED CHARGE IMAGES. If a photoemitter is to generate and store an electrical image, the image charges that are developed will be positive, since electrons will be lost from the surface by the photoemission process.

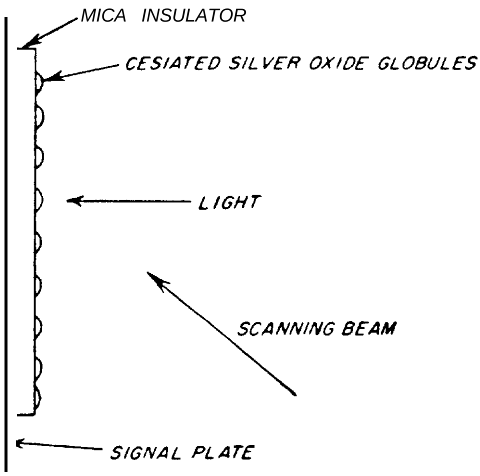

FIG. 11-4 Iconoscope mosaic. (*From Fink.*[1,†])

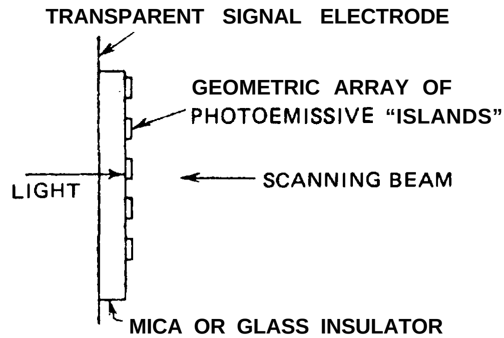

FIG. 11-5 CPS emitron mosaic. (*From Fink.*)

If storage of the image is to take place on the photoemitter itself, the photoemitter must have sufficient electrical resistivity to store the charge without significant leakage from one element of the picture to adjacent elements during the storage time of a single television field (16 to 20 ms). Photoemitters are generally good electrical conductors and therefore cannot store an image charge on a continuous sheet or film of photoemitter material.

Early camera tubes surmounted this problem by having the photoemissive material either in discrete particles or in a discrete geometric array of photoemitting patches. This presented construction difficulties, problems of electrical stability, and difficulties of scanning with an electron beam.

One type of tube, the iconoscope, used a mosaic consisting of small particles of photoemitting material on an insulating substrate (Fig. 11-4). Light absorbed by the photosensitive silver-oxygen-cesium photoemitter emitted electrons to a surrounding collector, and the isolated globules of the mosaic charged up positively in proportion to the light on each.

Another approach was to use a thin, semitransparent two-dimensional array of square patches of light-sensitive material. These were placed on a transparent insulator and transparent signal electrode (Fig. 11-5). This structure functioned in the same way as the mosaic shown in Fig. 11-4, except that the light entered from the side opposite the photoemitter. This greatly simplified the scanning process. It was made possible by the development of an exceedingly thin photoemitter so that electrons generated near one side of the material could travel through it and escape from the vacuum interface surface.

11.2.2 SECONDARY-EMISSION-INDUCED CHARGE IMAGES. A second method of developing a charge image by a photoemitter is to use the principle of secondary emission. Here the electrons are accelerated away from the photoemitter surface, which is a continuous film on the inside of the tube faceplate. The individual streams of electrons are focused on an insulating material that is also a good secondary emitter (Fig. 11-6).

The electrons can be focused by either magnetic or electrostatic fields, but it must be done with sufficient precision that each stream of electrons striking the insulator develops a charge that has the same spatial relationship on the insulator as the source of electrons on the photoemitter.

The secondary emission process is identical to the photoemission process, except that the incident energy is provided by electrons having energy of many hundreds of electronvolts rather than only the several electronvolts of energy available in visible-light

† Superscript numbers refer to References at end of chapter.

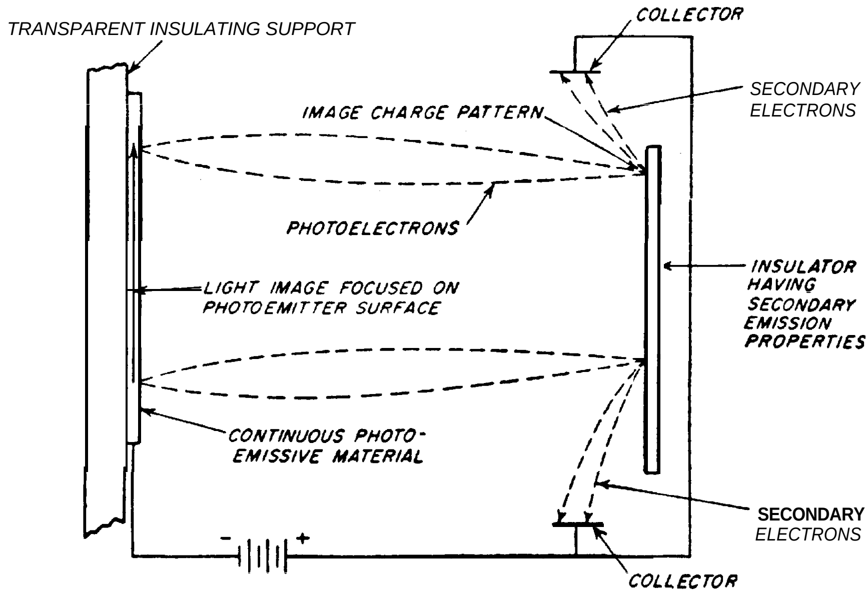

FIG. 11-6 Transfer of potential images by secondary emission. (From Fink. [1])

photons. The primary electrons penetrate into the material and transfer a portion of their energy to each electron with which they interact. If this energy is sufficient to free the electrons from the valance band and overcome the band gap (Fig. 11-1) and the electron can migrate to the surface of the material with enough energy to overcome the electron affinity of the surface, that electron can escape from the material as a **secondary**-emitted electron.

The charge pattern that is developed on the secondary-emitter insulator surface is positive if more secondary electrons are emitted than are incident on it from the stream of primary photoelectrons. The insulating surface must have high enough resistance to store the electron charges and prevent lateral leakage in the interval between successive scans of each portion of the image.

Secondary emission will take place at the surface of any material if the energy of the impinging electrons is high enough. Most materials have a secondary-electron-emitting characteristic similar to that illustrated in Fig. 11-7. At low energies, the bombarding electrons cause less than one secondary electron to be emitted for every primary incident electron, and a negative voltage will be built up on the insulator. When the energy of the primary electron is high enough so that more than one electron (on the average) is liberated, the charge developed on the surface will be positive. It is desirable to have positive-image charges developed by a television camera tube since positive charges can be more readily interrogated by an electron beam than negative charge patterns.

The process of generating charge images in a television camera tube can result in amplification. The gain at the secondary emitting surface is the secondary emission ratio minus 1.

The voltage chosen for acceleration of the photoelectrons determines the amount of gain. The gain reaches a maximum at a particular voltage for each material, and then decreases as the energy of the incident electrons is increased. This is caused by the electrons penetrating deep into the material where they lose their momentum by transferring energy to electrons in the

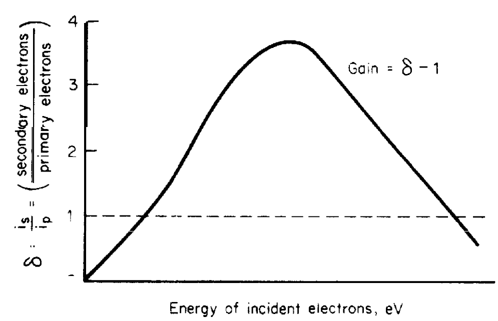

FIG. 11-7 Secondary-emission ratio of a typical surface.

material. These excited electrons generated deep within the material have a much lower probability of escape than electrons that are excited near the surface. In some materials the secondary emission ratio actually decreases below 1 at very high energies of the primary electrons.

Unlike a photon of light that transfers all its energy to a single electron as it is annihilated, a primary electron transfers some momentum to each electron with which it interacts and continues to do so till the electron is captured within the structure of the material. There is a wide spectrum in the energy of the secondary electrons emitted from the surface of a secondary emitter, as shown in Fig. 11-8. Many electrons have a low energy, in the range of several electronvolts. A few have much higher energies. The right-hand peak of the curve represents electrons that have an energy equal to that of the incident electron beam. In all probability these are primary electrons that are reflected from the surface without interacting with any electrons in the structure. Because of the wide range of velocities of the secondary electrons, it is difficult to image these electrons to another surface for further storage or amplification.

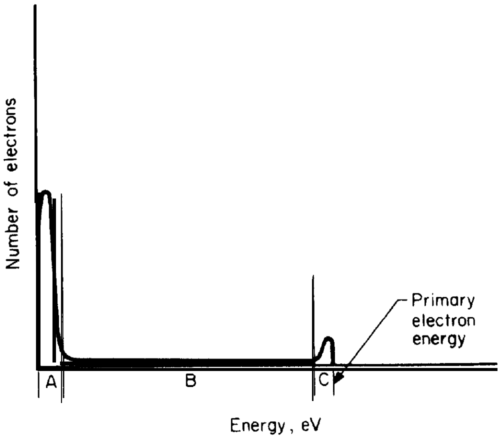

FIG. 11-8 Secondary-electron energy distribution.

11.2.3 ELECTRON-BOMBARDMENT-INDUCED CONDUCTIVITY. Electron-bombardment-induced conductivity is a natural extension of both secondary-emission-generated image charge and photoconductivity technology.

Here the insulating material of the secondary-emission-generated charge storage target is not used. In its place there is a material that exhibits high electron-bombardment-induced conductivity. This material is placed at the plane where the electrons generated by photoemission are brought to focus corresponding to the point on the photoemitter from which they were emitted (Fig. 11-9). The electrical conductivity is produced by the primary electrons penetrating the material and releasing electrons from the valance band into the conduction band. Typically, the photogenerated electrons from the photoemitter are accelerated to an energy of several thousand electronvolts before they strike the target.

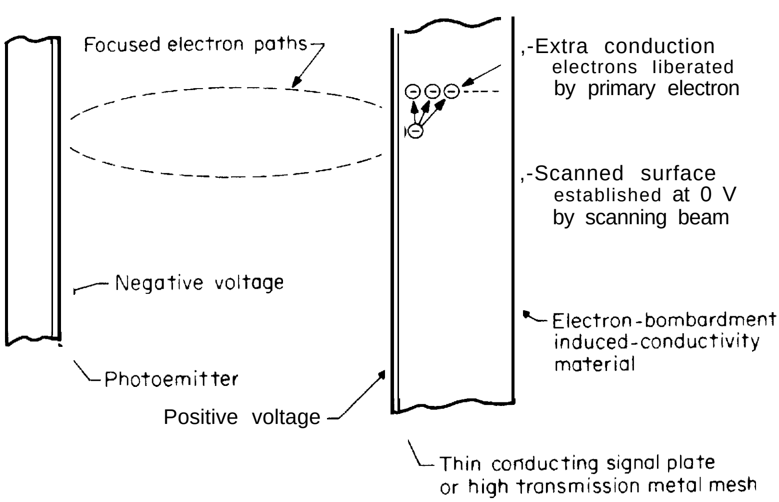

FIG. 11-9 Bombardment-induced conductivity.

Unlike photon-induced conductivity (where the photons are annihilated by transferring all their energy to a single electron), this process is not limited to one free electron per incident photon. Here the fast-moving electrons continue losing energy as they hit other electrons, until they are no longer able to excite any more into conductivity.

This process is capable of extremely high amplification since very high-energy primary electrons are needed to penetrate the signal plate and deep into the material. This energy is available for transfer to numerous electrons. Gains in the thousands of electrons can be achieved in practical camera tubes using this method of signal generation.

The secondary-electron bombardment-induced conductivity method to generate a stored-charge image is the same one used by photoconductive-sensitive camera tubes (see Sec. 11.2.4).

Materials having a narrow band gap (needed for photoconductors) are not necessary for electron-bombardment-induced conductivity. This is because the energy of the bombarding electrons can be in the range of many thousands of volts. Thus, large portions of the energy of the bombarding electrons can be transferred to the electrons of the material. These excited electrons can then either jump into the conducting band or, if there is enough energy left over, some can interact with other electrons in the valance band, which are in turn pushed into the conducting band. The gain of this process (conducting electrons/primary electrons) can be varied by varying the velocity of the primary electrons.

A widely used bombardment-induced conductivity target is silicon. This silicon target is virtually identical to the one used as a light-sensitive photoconductor (see Sec. 11.4.4). The charge image is generated from the electrons (and holes) that are freed as charge carriers in the silicon and stored as charges on the diode array.

11.2.4 PHOTOCONDUCTIVE-GENERATED CHARGE IMAGES. A **photoconductor** can be used to develop a charge image which is then stored on its surface.

To utilize the property of photoconductivity, an electric field must be impressed across the photoconductor. The usual way to do this is to deposit photoconductive material on an electrically conductive and transparent substrate (Fig. 11-10). In order to develop a positive charge pattern easily interrogated by an electron beam, a positive voltage is applied to the signal electrode. A more negative voltage is established on the opposite side by an electron beam (see Sec. 11.2.5).

To be effective as a charge-pattern generator and storage medium, the surface on which the charges are to be stored must have high resistivity. This prevents the charges from being lost laterally during storage. The bulk resistance of the material must also be high enough to prevent loss of the voltage across the thickness of the layer during intervals between successive scans. The equivalent electrical circuit of a photoconductor used in a camera tube is shown in Fig. 1 1-l 1.

The voltage E that is applied across the photoconductor is called the *target voltage.*

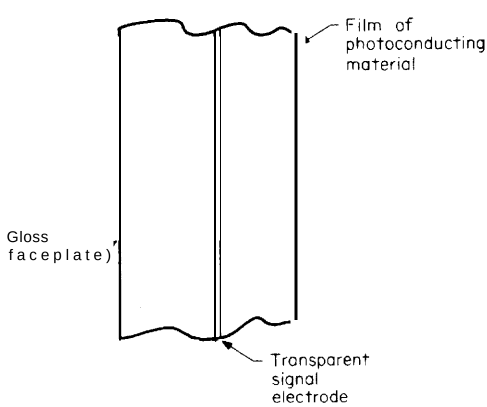

FIG. 11-10 Cross section of a camera tube target using a photoconductor.

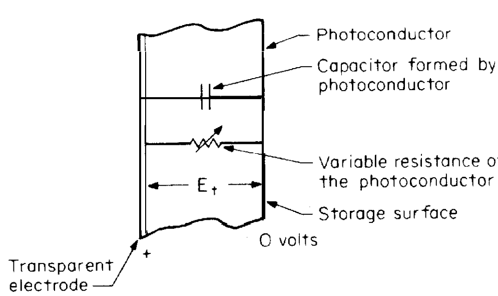

FIG. 11-11 Equivalent electrical circuit of a photoconductor.

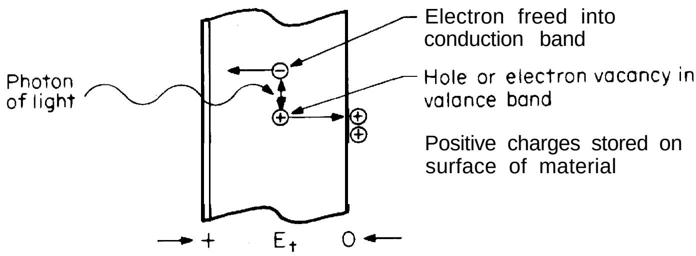

FIG. 11-12 Photon-generated electron-hole pair liberated in a photoconductor, producing stored positive charges on the photoconductor surface.

When light is absorbed in the photoconductor, the effective resistance decreases and more current flows through the resistor. This resistor discharges the capacitor, and a more positive voltage appears on the storage surface where light is absorbed than where there is little or none. The positive voltages that are built up on this surface are in proportion to the illumination at each portion of the image which is focused on the plane of the photoconductor.

Another way of understanding this process is to consider the photoconductor in terms of the dynamics of energy bands of the material and photon energy (discussed in Sec. 11.1.2) as visualized in Fig. 11-12. Under the influence of the electric field within the material, photons liberate electrons and holes. The electrons are free to move toward the positive electrode in the conduction band, and holes or electron vacancies are free to move toward the negative surface. The positive charges are stored on the storage surface and constitute the charge image that is then used when generating the television picture signal.

Several necessary properties of the photoconductive material are implied by the discussion of the method of operation.

The first is a band gap narrow enough that all photons in the spectrum in which the device is to be sensitive have enough energy to boost electrons across this band gap.

Second, the material must optically absorb the light that is to be detected. The resistance of the material must be high enough on the storage surface that the charge integrity is maintained at each point between successive scans; it is preferable that the resistance in the dark be high enough so that very little signal is generated in the absence of light.

Third, there must be few trapping states in the photoconductor that can slow up or delay the transit of charge carriers from their point of excitation to their destination.

Fourth, the carriers should have good mobility through the material so they can be swept through before they recombine with charge carriers of the opposite polarity.

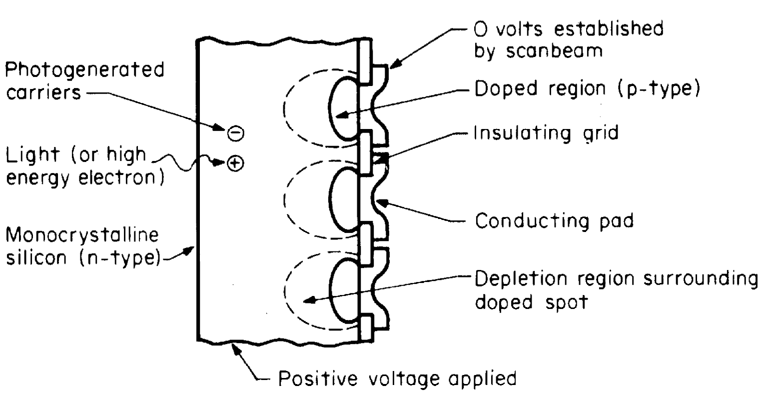

FIG. 11-13 Cross section of a silicon diode array photoconductive target.

Though high-resistance materials are best, low-resistance materials that are good photoconductors in other respects can be used in a television camera tube. Special structures, such as silicon diode arrays, are used in some tubes. Figure 11-13 illustrates such a structure. Silicon has good electrical conductivity and can serve as its own contact electrode. By reverse biasing the diode formed by the p-doped dots in n-type silicon, the resistance between the adjacent diodes, and between the diodes and the substrate, can be made high. A high electric field exists in the depletion region around each diode dot. Since the diodes are reverse biased, very little dark current flows through the depletion region.

When light (or high-energy electrons) enters the silicon, charge carriers are generated. The material is n-type and has poor mobility for p-type carriers. It is processed in such a way that the hole mobility and lifetime are great enough for most of the p-carriers to survive long enough to diffuse through the silicon and enter the depletion region. Here they are accelerated to the diode doped region and establish a positive charge on the contact pad.

11.2.5 GENERATION OF VIDEO SIGNALS BY SCANNING. In a storage-type television camera tube, the signal is developed by an electron beam that scans the stored charge images that are produced by photosensitivity. The assembly on which these charges are stored is called the *target*. At the present time all camera tubes use a low-velocity scan beam.

11.2.6 LOW-VELOCITY SCANNING. Low-velocity scan does not pertain to the speed with which the beam progresses across the picture area of the target in the television scanning process. Instead, the term indicates that the electrons in the beam are moving slowly as they approach the stored charges of the charge image.

The purpose of the scanning electron beam is to deposit electrons on the positively charged areas of the stored charge image that correspond in voltage to the brightness of the scene at that point. The use of a low-velocity beam assures that most of the electrons of the beam will land on the stored charge until its voltage drops to near zero and that very few secondary electrons will be emitted from the surface, If the kinetic energy of the beam electrons is high when they land on the storage surface, secondary electrons may be emitted from the surface, defeating the positive-charge neutralizing process.

The element of the storage target being interrogated by the scanning beam (Fig. 11-14) develops a positive voltage in the interval between successive scans of that spot. The magnitude of the voltage depends on the capacitance C of the element and the quantity of positive charge being developed

$$C_t V = Q$$

The scanning beam deposits electrons on this element and almost instantaneously drives the voltage down to zero in interval *BC* in Fig. 11-15. It then continues to the next portion of the scan image, where the process is continued. The point that was just neutralized will start to charge positively again along the curve *CD* if light is still present at that portion of the image. At time t_2 when that element is scanned again and the process will be repeated, that portion of the target capacitance will be recharged to its original voltage.

A problem in terminology often develops when describing this process. The stored charge image is a positive voltage with respect to the reference, which is the cathode of the electron beam. However,

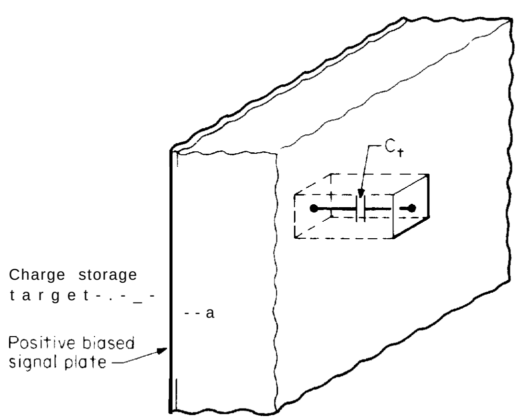

FIG. 11-14 Charge storage target showing capacitance of individual areas storing an image charge.

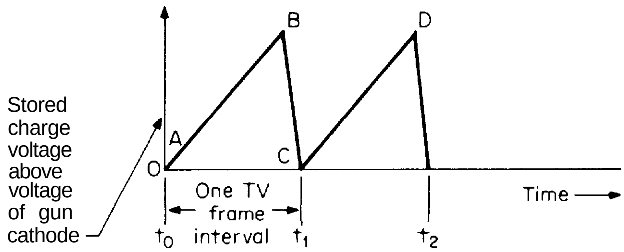

FIG. 11-15 Discharging and recharging of the capacitance of an elemental area on a storage-type target.

the positive-image charge voltage is actually a result of *discharging* the target capacitance. The electron beam is usually said to be "discharging" this positive voltage and restoring it to zero volt. In actuality it is *recharging* the target capacitance.

A television signal may be developed by this process in two ways. The first is by amplifying the current that flows in the signal plate electrode of the target. The second is by capturing the return beam that is unused in the stored-image charge neutralization process.

The method of signal generation using the signal plate current can be visualized in Fig. 1 l-16. Figure 11-16a illustrates what takes place in the time interval between scans of this point on the target of a photoconductive tube. The photo-induced current is flowing through the resistance R_p and the target capacitance C_t. No net charge is being added to the target assembly, nor does any of this current flow into or out of the signal plate at this time. As the capacitor C_t is being partially discharged, it becomes more positive on the scanned surface. In Fig. 11-16b the scanning beam deposits electrons on the surface. This flow of electron current recharges the capacitor, and an equal current flows through the signal plate to the amplifier. In the absence of light, little or no buildup of voltage occurs on the scan surface; consequently no current is developed when the beam scans that spot. The current that flows out of the signal electrode always flows in the same direction and is zero in the absence of light. This is extremely important since there is always a zero dc component in the video-signal current when no beam is landing on the target, and the absolute level of the current flowing out of the signal plate relates directly to the voltage of the charge pattern that is being scanned by the electron beam.

A low-velocity beam is achieved by designing the surface which is scanned so that the secondary emission ratio of the scanned surface is less than 1 at the highest voltage applied to the target. Even if the beam is accelerated and formed at very high voltages

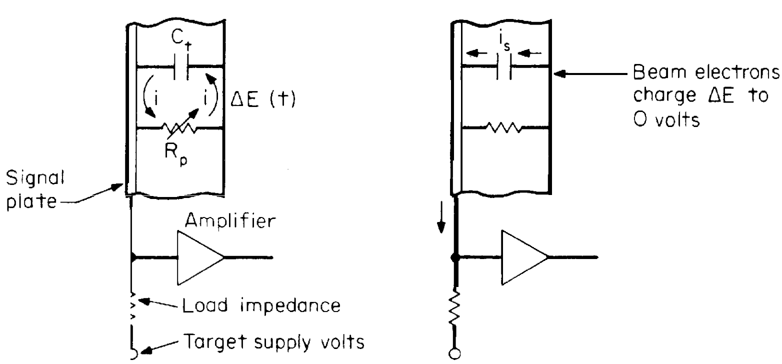

FIG. 11-16 (a) Currents flowing in a photoconductive target elemental area while the target is integrating a charge ΔE because of light-induced change in the photoconductor resistance. (b) Current flow when a low-velocity electron beam is interrogating the element.

and producing high beam velocities in the electron gun, it will be decelerated as it approaches the target surface. Maximum velocity (expressed in electronvolts) the beam will have as it lands on the scanned target is the voltage of the scanned surface with respect to the cathode of the electron gun from which the electrons are emitted. If the secondary emission of the surface is less than 1, more electrons will be deposited than emitted, and the surface will be charged in a negative direction until the voltage is nearly equal to the voltage on the emitting cathode of the electron gun. When this condition is reached, no more electrons will be deposited, and the unused electrons of the beam will be accelerated back toward the positive gun electrodes.

In a photoemissive target, or when a charge is being developed on a storage target by the process of secondary emission, current flows in both directions into the signal plate. There is an inflow of electron current caused by the photoelectrons or secondary electrons, and there is an outflow of electrons caused by the scanning beam recharging the stored-image charge pattern. See Fig. 11-17. This presents problems in establishing a proper dc or black-level reference, especially if the scene illumination is not constant. The signal current, however, is developed by the beam current as illustrated in Fig. 11-16.

112.7 RETURN-BEAM SIGNAL GENERATION. When a low-velocity scanning beam is used in a camera tube, it may be convenient to utilize the return beam. The return beam is the portion of the beam that does not land on the target during the process of scanning the stored charge image on the target. The electrons that are not used to recharge the capacitance of the target are slowed to a stop in front of the target and then returned toward the electron gun, following roughly the same path that the scanning beam took as it passed through the gun. See Fig. 11-18. This return beam has information that is equal and opposite in polarity to the signal current flowing through the target.

This return beam can be steered by electron optical means and captured on an electrode, where it is channeled as a current to an external amplifier. Or it can be amplified within the device before it is collected in an output electrode to be channeled to the external amplifier.

This return beam has additional noise in addition to any noise in the signal component of the return beam. This noise is contributed by the random noise in any excess beam current beyond that required to neutralize the charge image on the target.

The return beam actually has two components. One is a reflected component; the other, a scattered component. The reflected electrons are reflected mirrorlike from the surface; the other electrons are scattered by interacting with the charge pattern on the target.

The reflected electron beam has a maximum amount of beam reflected from dark portions of an image. Consequently there is a lot of noise in the dark portion of the image, but very little in the light.

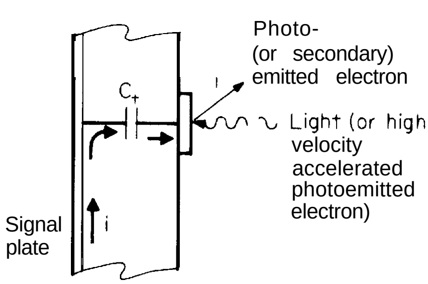

FIG. 11-17 Current flow in target structure during integration interval (photoemissive or secondary emitting storage target).

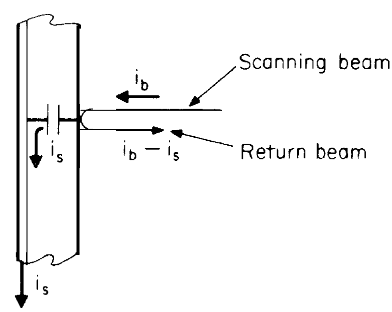

FIG. 11-18 Return-beam and scanning-beam current relationships.

The opposite occurs with the scattered beam. Here the maximum number of electrons are scattered by the positive charges on the target, and very little scattering takes place on the small charges representing black. As a consequence there is little noise in this component of the return beam in the dark, and maximum noise is present at highlights where its visibility is lessened.

The scattered and reflected portions of the return electron beam can be separated by unique operation and separation methods, and the most desirable portion of the return beam can be used to constitute the video signal. (See Image Iconoscope in Sec. 11.3 and Ref. 2.)

11.2.8 **HIGH-VELOCITY SCANNING.** High-velocity scanning takes place when the beam lands on the target with very high energy and maintains the scanned surface at high voltage by the process of secondary emission. More secondary electrons are emitted than the number of electrons on the primary scanning beam. As a consequence the target surface charges positively when bombarded by the electron beam. The voltage increases as secondary electrons are emitted and then collected by a more positive electrode. When the surface reaches, or slightly exceeds, the voltage of the collector electrode, secondary electrons leaving the target are repelled by the collector and fall back on the target. When they land, they unavoidably reduce the positive stored image charges there. A video signal can be generated in this high-velocity scan process, as illustrated in Fig. 11-19.

There is a net change in charge of the elements as they are scanned by the beam. The areas that were charged positively by photoemission have a lesser change of charge when scanned than do the unilluminated areas. This change is accompanied by a varying charging current flowing through the capacitor which is formed by photosensitive elements spaced from the signal plate by a dielectric insulator. These currents flow through the deflection plate, and in and out through the video amplifier, and constitute the video signal.

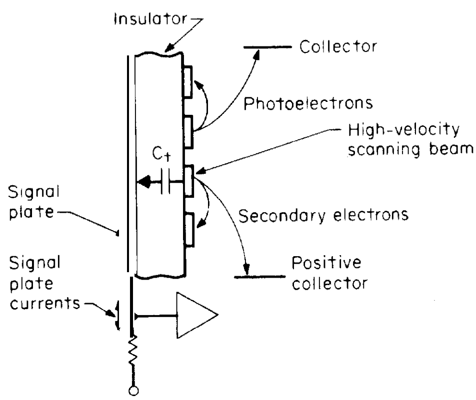

FIG. 11-19 Flow of currents in and from a high-velocity scanned target.

If one has difficulty determining the resulting magnitude of the video signal from this description, it is quite understandable. The camera tubes using this process had the same difficulty in producing a signal that was a faithful representation of the absolute, or even the relative, amount of light at each portion of the scene. Instead of all the emitted photoelectrons going to the collector, some fell back on unpredictable portions of the storage area. Secondary electrons followed similar unpredictable paths, and the output signal consequently lacked fidelity to the scene brightness at each point. However, these devices are capable of good resolution, since the charges do not migrate laterally across the storage surface.

11.3 EVOLUTION AND DEVELOPMENT OF TELEVISION CAMERA TUBES

11.3.1 **NONSTORAGE TUBES.** The early television camera tubes all used photoemitters as light detectors. The first one was a nonstorage device, the *image dissector.* It was reasonably uncomplicated. The operating principles are illustrated in Fig. 11-20. A photocathode film (photoemitter) was formed on the inside of the faceplate. The elec-

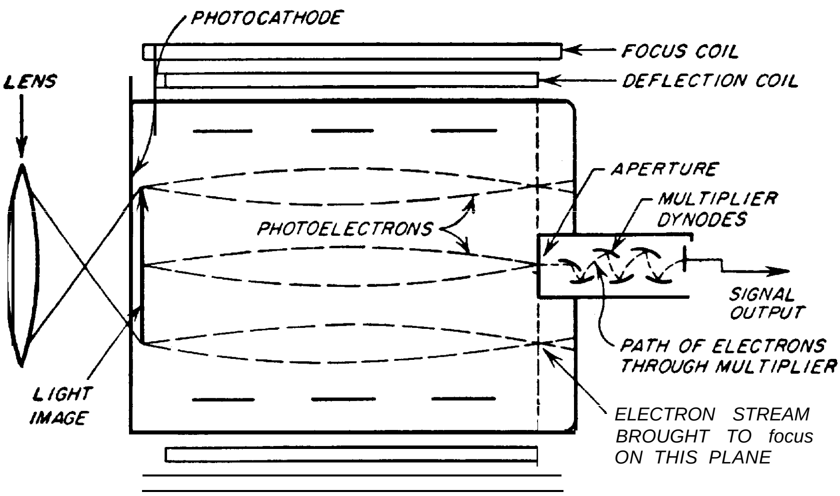

FIG. 1 1-20 Operating principles of the image dissector. (From Fink)

trons emitted by light were accelerated by a uniform electric field. They were then focused on a plane at the opposite end of the field by a uniform axial magnetic field produced by a solenoid focusing coil. A small aperture followed by a secondary electron multiplier structure was positioned at the center of the plane of focus. Focused streams of electrons from the photocathode were deflected across the aperture by horizontal and vertical magnetic deflection coils. Those electrons that passed through the aperture were multiplied by a factor of several thousand by the electron multiplier. The electrons not passing through the aperture were lost.

There were several disadvantages to this tube, the most significant of which was the high light level required to achieve an adequate signal-to noise ratio. A large amount of information was lost because only the photoelectrons emitted from each point of the image at the time the point was being interrogated could be used.

11.3.2 STORAGE TUBES

Iconoscope. The next camera tube to evolve was a storage type. The *iconsocope* (Fig. 11-21) tube had a mosaic photoemitter consisting of isolated granules of cesium silver oxygen on an insulating mica substrate, with a conducting signal plate on the opposite side. The light image was focused on the same side on which the charge image of the mosaic was scanned. This tube utilized a high-velocity beam that scanned the surface at an angle of approximately 45°. It was much more sensitive than the image dissector since it stored the charges developed by the photoemission process between successive scans. The output signal was developed as capacitively coupled signal currents flowing through the signal plate. These currents were directly amplified by an external low-noise amplifier (see Sec. 11.2.8, High-Velocity Scanning).

The iconoscope has good resolution but suffered from imprecise signal levels. These were caused by both photoelectrons and secondary electrons raining back randomly on the storage surface, thus discharging some of the stored image charges. The tube required illumination levels on the photosensitive mosaic of the order of 5 to 10 fc (50 to 100 lux).

Image Iconoscope. A further evolution was the *image iconoscope* (Fig. 11-22). This tube had an image section with an efficient continuous-film semitransparent photocathode on the inside of the faceplate. The streams of light-emitted electrons from this surface were focused on the plane of the storage plate (target) by the axial magnetic-focusing field. This field was produced by focusing coils in the same manner as in the image

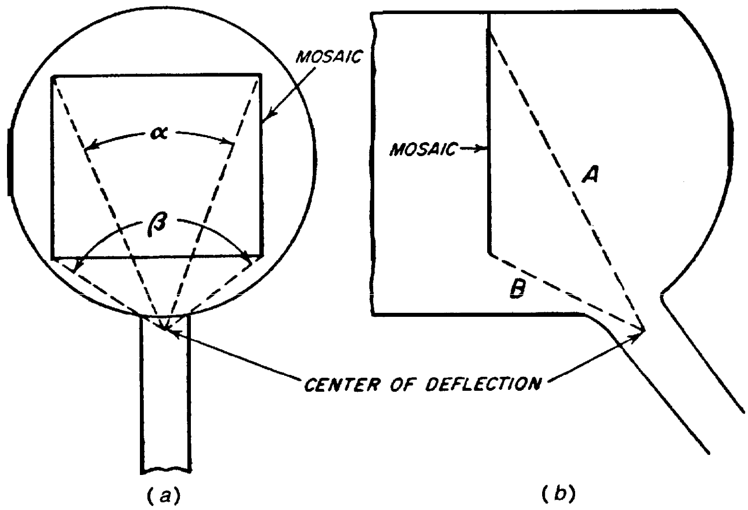

FIG. 11-21 Iconoscope deflection geometry (a) front view and (b) side view, where α and β are horizontal deflection angles of the scanning beam, A at the top, and B at the bottom, of the raster. *(From Fink.* [1]*)*

dissector. The electrons were accelerated by a uniform electrical field and struck the storage target with an energy of several hundred electronvolts. They formed a positive image charge on the insulating surface of the target by the process of secondary emission, producing a gain in level in the process (see Sec. 11.2.2). The video signal was developed by

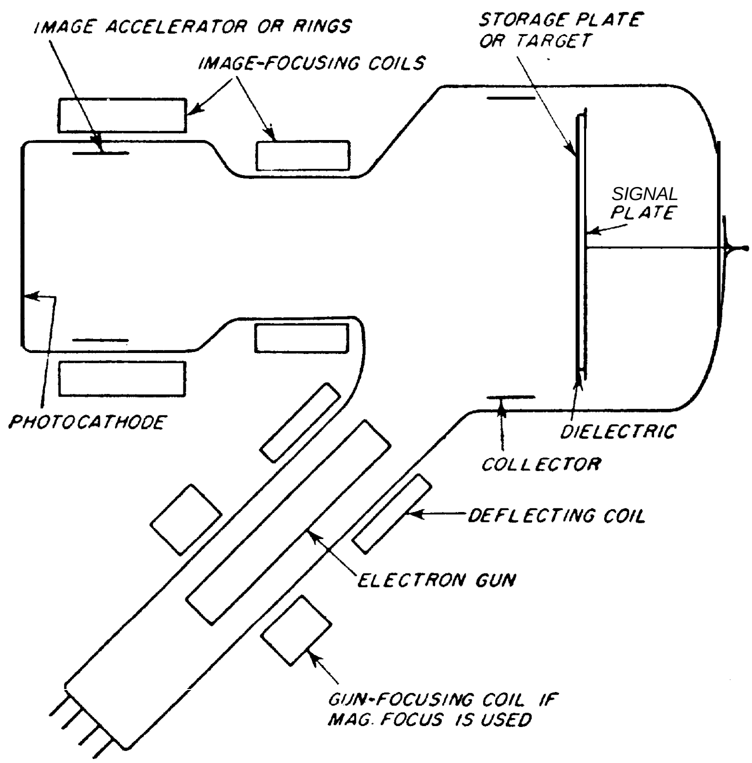

FIG. 11-22 Schematic diagram of the image iconoscope and its associated components. (From *Fink.*)

scanning the storage target with a high-velocity scanning beam at an angle of about 45°, in exactly the same manner as in the iconoscope.

Both of these devices had a unique virtue not present in the image dissector. That tube had a linear relationship between input light and output signal. But in the iconoscope and image iconoscope the output signal versus input light was less than linear. In other words, the highlights were compressed and the signals more closely matched the nonlinear input-voltage output-brightness characteristics of the picture display tubes. This produced more natural tones in the picture.

Orthicon and CPS Emitron. The next development was a family of tubes called *orthicons* and *CPS emitrons.* These tubes used a target with a mosaic-type photoemitter on one side of an insulating support membrane and a transparent signal plate on the other side. The target was scanned by a low-velocity electron beam.

The name orthicon was derived from the fact that the beam landed orthogonal to the target in the low-velocity scanning process, whereas the CPS emitron takes its name from the process of cathode-potential-stabilized target scanning.

The orthicon photoemitter was composed of isolated grains of light-sensitive material deposited on the insulator, while the CPS emitron used a precise mosaic of squares of a semitransparent photoemitter. This structure was formed by evaporating the base material of the photoemitter through a fine mesh. Both of these tubes produced high-resolution pictures with precise gray scales.

The signal from these tubes was taken from the signal plate and fed directly to a video amplifier (see Sec. 11.2.6).

A cross-sectional view of a CPS emitron (Fig. 11-23) illustrates the configuration of these tubes. It is extremely important that in low-velocity scan the beam land perpendicular to the target and alignment coils were developed to correct for any off-axis alignment of the electron beam. In addition, fine and precise high-transmission mesh structures were developed to produce a uniform deceleration field at the target.

This class of tube had two drawbacks. The first was instability caused by highlights. If an abnormally bright highlight raised the charge on the mosaic photoemitter more than a few volts during the storage interval between scans, the scanning-beam electrons would land with sufficient velocity to emit more secondary electrons than the number landing from the beam. The surface would then charge positively in a runaway manner and progressively wipe out the picture across the target. The tube would then have to be shut down and restarted to restore a normal picture.

Secondly, photoemission from the target caused an electron current to flow into the signal plate as electrons were emitted from the mosaic elements. If the illumination came from fluorescent lights, for example, this produced a low-frequency ac signal in the signal plate, which was amplified by the video amplifier. This unwanted signal was added to the video signal currents which were induced in this circuit when the scanning beam deposited electrons on the positively charged mosaic elements, and restored them to the cathode potential of the electron-gun cathode.

These tubes used a second-electron optical feature. The beam went through multiple nodes of focus as it progressed from the gun to the target. This aided the deflected scanning beam to land perpendicular to the target and cut down on the amount of magnetic focus field and deflecting power required.

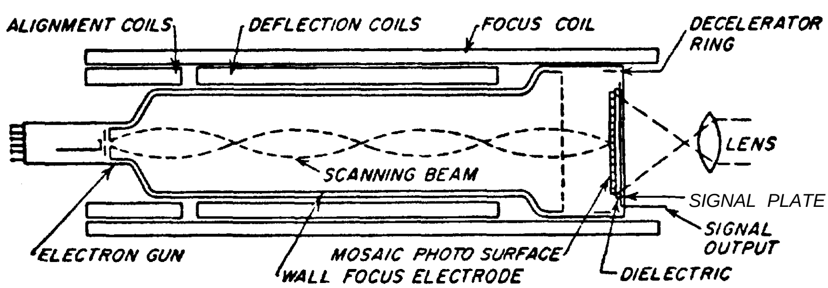

FIG. 11-23 Diagram of CPS emitron. (From Fink[1])

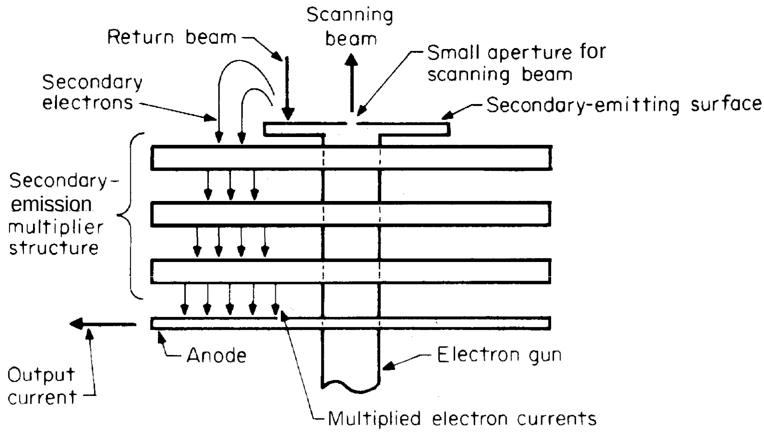

FIG. 11-24 Electron gun and return beam secondary emission multiplier.

Multiplier Orthicon. The next stage in the evolution was the multiplier orthicon. This tube used the return beam to produce the video signal. (See Sec. 11.2.7.)

The return beam in this type of electron-optical system returns more or less along the same path as the outgoing scanning beam. It is amplitude modulated by the extraction of electrons in the target scanning process. This return beam is directed into an electron multiplier structure, which is situated as shown in Fig. 11-24. The secondary electrons emitted from the front surface of the gun are directed into the first dynode of the multiplier structure. They are amplified approximately 1000 times before being collected on the anode, where the signal is then fed into an external amplifier. This method of amplification is essentially noiseless and raises the amplitude of the signal above the noise of the first amplifier stage.

Return beam amplification improves the signal-to-noise ratio of the output signal, compared with the signal-to-noise ratio achieved when the target readout signal is fed directly into an amplifier. There is a difference in the character of the noise. The noise energy in the return beam signal is constant at all frequencies. On the other hand, the noise in the spectrum of the directly amplified target signal is proportional to the frequency. (See the discussion of video amplifiers in Sec. 11.5.6.)

Image Orthicon. This tube of advanced design evolved from the multiplier orthicon with the development of a two-sided target structure. This solved the problems of target instability and allowed the use of a more efficient continuous-film semitransparent photocathode. This tube also eliminated the problem of ac photocurrents produced by fluorescent lights.

The image orthicon consists of three separate sections, each of which operates differently from the others. They are termed the *image section,* the *scanning section,* and the *multiplier section.* (See Fig. 11-25.) The action of the image section is considered first.

The image to be televised is focused on the transparent photocathode on the inside of the faceplate of the tube. This faceplate is maintained at a negative voltage of approximately 450 V. The electrons are emitted from this photosurface at each point in proportion to the illumination at that point and are accelerated toward the target-mesh assembly, which is maintained at nearly zero potential. The G_6, or image accelerator electrode, serves by rapidly accelerating the electrons to prevent them from being deflected by extraneous magnetic fields, and serves to maintain geometric symmetry of the image created on the target mesh assembly. The electrons emitted from each point of the photocathode are brought into sharp focus at a corresponding position on the target by the action of the electrostatic field of the electrodes of the image section, and the axial magnetic field produced by the external focus coil. The target mesh assembly consists of an

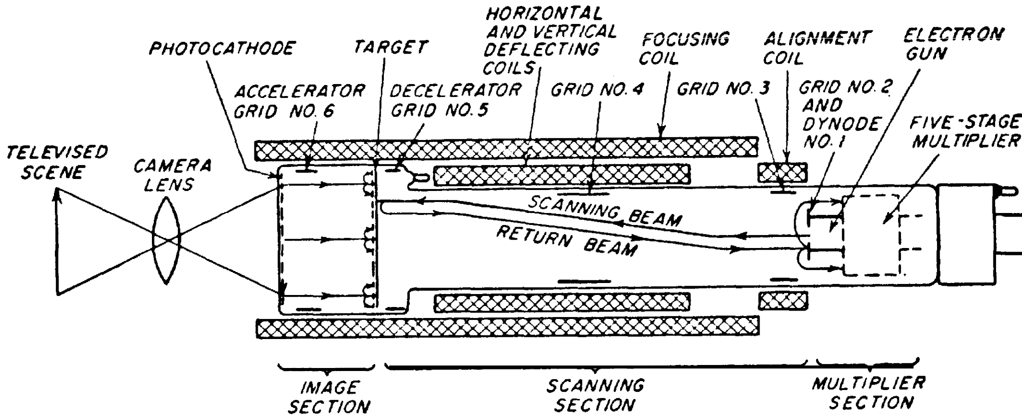

FIG. 11-25 Schematic arrangement of the image orthicon. *(From Fink.)*

extremely fine mesh closely spaced to a thin glass membrane. Most of the photoelectrons pass through this mesh and strike the glass target,, causing secondary electrons to be emitted. These secondary electrons are collected by the target mesh, which is maintained at a slightly positive potential with respect to the target. This action produces a positive charge on the target glass and also produces an amplification of charge that is equal to the secondary emission ratio minus 1. The charge image on the glass is stored until neutralized by the scanning beam.

The scanning section consists of an electron gun which produces a high-resolution beam. This beam scans the target of the image section under the influence of the transverse magnetic field produced by the deflection coils located along the neck of the tube. The target consists of a thin membrane of semiconducting glass. The resistivity of this glass is of particular importance, since it must be low enough that the charge on the mesh side can migrate through the glass in the interval between successive scans of the tube, yet high enough that the lateral leakage of the stored charge of one element to the adjacent one is negligible. The electron gun consists of a thermionic cathode which is maintained at ground potential, a control grid, and an accelerating grid with a limiting aperture (G_2) that forms an extremely sharp and collimated electron stream. This beam travels through the tube at a velocity determined by the G_4 or wall electrode voltage. The electrons within this beam go through several loops of focus and are brought to sharp focus on the target after passing through the decelerating field of the G_5 electrode. They land with nearly zero velocity on the gun side of the target. The electron beam scans the surface of this glass and deposits sufficient electrons on the charged areas to neutralize the charge on the target under the beam, and drive it down to the potential of the cathode of the electron gun. When this condition is reached, no more electrons can be deposited, and the remainder of the electrons return toward the electron gun. Figure 11-26 illustrates the action of the target-mesh assembly and the discharge of the target charge by the electron beam.

The scanning beam is caused to return substantially along the same path for its return trip as for the scanning trip. This return beam has been amplitude modulated by the loss of electrons to the charges on the target, and constitutes the video signal information that is ultimately taken from the tube. The return beam scans a small area of the surface of the first dynode (which is also grid No. 2), the surface of which has a high secondary emission ratio. The secondaries, emitted when the beam strikes the first dynode, are attracted toward the multiplier stages by the influence of the G_3 electrode and the field of the second dynode. These multipliers are made in the shape of a pinwheel, and as such channel the electrons efficiently through successive multiplier stages to the anode. The total current gain in this multiplier is between 500 and 1000.

The optical input may use conventional components because the useful area of the photocathode is 1.6 in (41 mm) in diameter. This corresponds to the same area as used

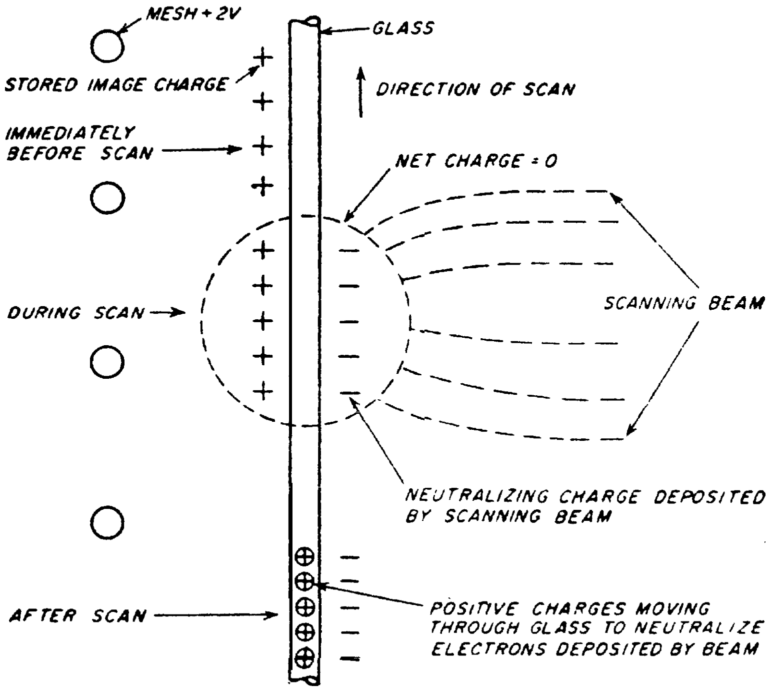

FIG. 11-26 Illustration of the target charge and discharge cycle of the image orthicon. *(From Fink.*[1]*)*

for double-frame 35-mm film. The photocathode can be composed of a variety of different semitransparent alkali metal-based photocathode surfaces. It is deposited directly on the inside of the faceplate of the tube.

The signal output of the image orthicon is in the order of 10 μA peak to peak The signal developed across the load resistance of the anode is black negative and white positive.

The output impedance of the multiplier is very high in its resistive component and is essentially a constant-current generator. The shunt capacity to ground of the multiplier anode is approximately 12 pF. The signal contains fairly accurate black-level information during retrace and may be coupled directly to the preamplifier with a capacitor, since the anode potential is normally operated at a high voltage.

The signal-to-noise ratio of the signal developed by the image orthicon is determined by the shot noise in the scanning beam. The signal-to-noise ratio, therefore, varies as the square root of the beam current necessary to discharge the target charge. The signal-to-noise ratio of the image orthicon tube is in the range of 36-dB peak signal to rms noise. The noise energy distribution is flat, having equal components in all portions of the video frequency band utilized. Maximum noise is in the black portion of the signal.

The basic light transfer characteristic is shown in Fig. 11-27. The knee of the curve represents the point where the target charges up to the potential of the mesh and is stabilized by secondary-emission mechanics to this potential. When this point is reached, the secondaries from the target are no longer collected by the mesh, but are free to be redistributed over the adjacent areas. This characteristic is important because it limits highlight signals and prevents the camera tube from becoming unstable in the presence of extreme highlights.

This is a rough interpretation of the stabilizing action of the image orthicon target-mesh assembly. The action is modified by the nature of the velocity distribution of the secondary electrons emitted by the target when bombarded by the photoelectrons. Secondary electrons with low velocities are collected by the mesh, or fall on adjacent areas

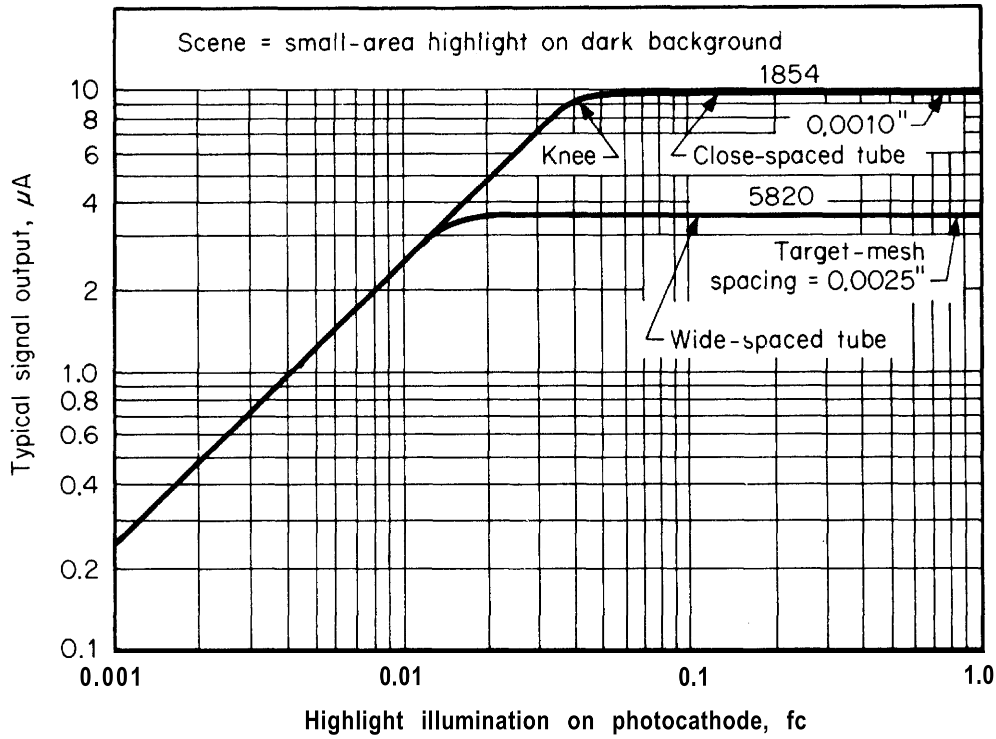

FIG. 11-27 Transfer characteristic of wide-spaced and close-spaced image orthicon tubes. (1 fc = 10.76 lm/m^2.) (From *Fink.*)

of the target and discharge these areas toward black. This enhances the apparent contrast and resolution of the picture. Secondary electrons with high velocities travel further from their point of origin and have sufficient energy to produce a positive spurious image charge.

The light transfer characteristic of the image orthicon is complex, considering these scattered secondary electrons, particularly when operated with the highlights substantially over the knee of the curve. The signal output of any portion of a scene is modified by the influence of the adjacent areas when operated in this manner. Operation with the highlights over the knee has some advantages. It produces control of the average transfer characteristic. Operation with twice the amount of light necessary to raise the highlights of the scene to the knee produces a signal that is nearly complementary to the characteristics of the kinescope and produces normal and pleasing tone rendition. The average gamma characteristic follows a 0.5 to 0.6 power law in this case.

Use of image orthicons in color cameras presents a different problem, requiring a predictable gamma or light transfer characteristic. A constant-gamma characteristic can be corrected electrically by compression or stretch circuitry. Random electron redistribution cannot be tolerated, since it will differ from color to color, dependent upon the amount of highlight energy in each color band of the scene.

Therefore the image orthicon in a color camera must be operated so that accurate colors can be reproduced. For this reason a high-capacity (close-spaced) target mesh structure tube is used, to extend the linear range of the signal-transfer characteristic.

Resolution of the tube is primarily limited by crosstalk of deflection fields into the image section. These fields cause a slight transverse motion of the photoelectron streams from the photocathode and degrade the fine-detail resolution. External shielding of the image section from these deflection fields must be provided for both the line and field frequencies. Resolution is also affected by the operating temperature.

Image Isocon. The image isocon is an advanced version of the image orthicon. It is designed to produce a better signal-to-noise ratio and to operate at lower light levels than the image orthicon. It accomplishes this by a more efficient use of the video information contained in the return beam. Unlike the image orthicon, it has practically no noise in the black portions of the signal.

The design of the image isocon is based on the discovery that the return scanning beam has two components, a reflected component and a scattered component, as illustrated by Fig. 11-28. The reflected electrons are the ones that do not land on the target, but are instead reflected mirrorlike from the target when they do not actually land on the target. When a charge is present on the target, a large number of electrons interact with this charge. Those that do not actually land are scattered by the electric field produced by the highlights of the stored image. If the beam is *misaligned* so that it approaches the target at a slight angle to the perpendicular, the reflected electrons will return along a slightly different path from that of the symmetrically scattered electrons.

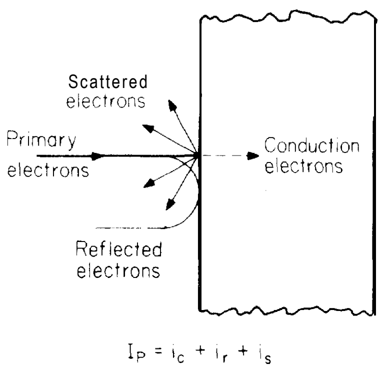

FIG. 11-28 Beam-current distribution of target of both image orthicon and image isocon. *(RCA Corp.)*

Figure 11-29 illustrates the paths of these different beam components and how they are separated in the return process. The return reflected beam is steered through the same aperture through which the primary beam passed. The scattered electrons strike the first dynode of the internal electron-multiplier section of the tube and are used as the video signal. The highest video-output current signal is in the highlights, while practically zero current is produced in the low lights. The polarity of the signal is therefore opposite to that of the image orthicon signal. Figure 11-30 illustrates an image isocon tube, its internal components, and the external deflecting, focusing, and aligning circuits required to operate this device.

The isocon is designed to handle a wide range of scene content. The knee characteristic limits the signal range of highlights, and the low noise at low light levels of a scene allows a wide contrast of information to be produced in the video signal. This tube is particularly useful in systems where very low light information must be seen in the presence of high-contrast highlights. It is used for outside nighttime surveillance in the presence of lights in the field of view, and for x-ray inspection systems where there are areas of very high and very low x-ray absorption in the field of view. It is made as 3- and 2-in-diameter bulbs with image facemats of 36.6 by 27.4 mm (45.7 mm diagonal) and 28.8 by 21.6 mm (36 mm diagonal), respectively.

Image isocon performance can be extended further to low light levels by coupling an image intensifier stage to the input of the tube. This is usually done by building the tube with a fiber-optic input window and butting an image intensifier tube with a fiber-optic output window to the image isocon fiber-optic faceplate.

Silicon Intensifier Tube. The silicon intensifier tube (SIT) is used where performance is expected at extremely low light levels that vary from very low light to daylight (see Fig. 11-31). The tube operates on the principle of electron bombardment-induced conductivity. This produces a high gain in the number of electrons stored at the target (see Sec. 11.2.3).

Typically the gain of the device can be varied from 10 to 1600. The gain at the target varies linearly with the voltage across the intensifier section (Fig. 11-32). This tube can produce a signal in medium light levels that is limited by the noise in the electrons generated by the photons interacting with the photoemitter. At lower light levels, noise in the signal is limited by the amplifier input noise, and at higher light levels by the loss of

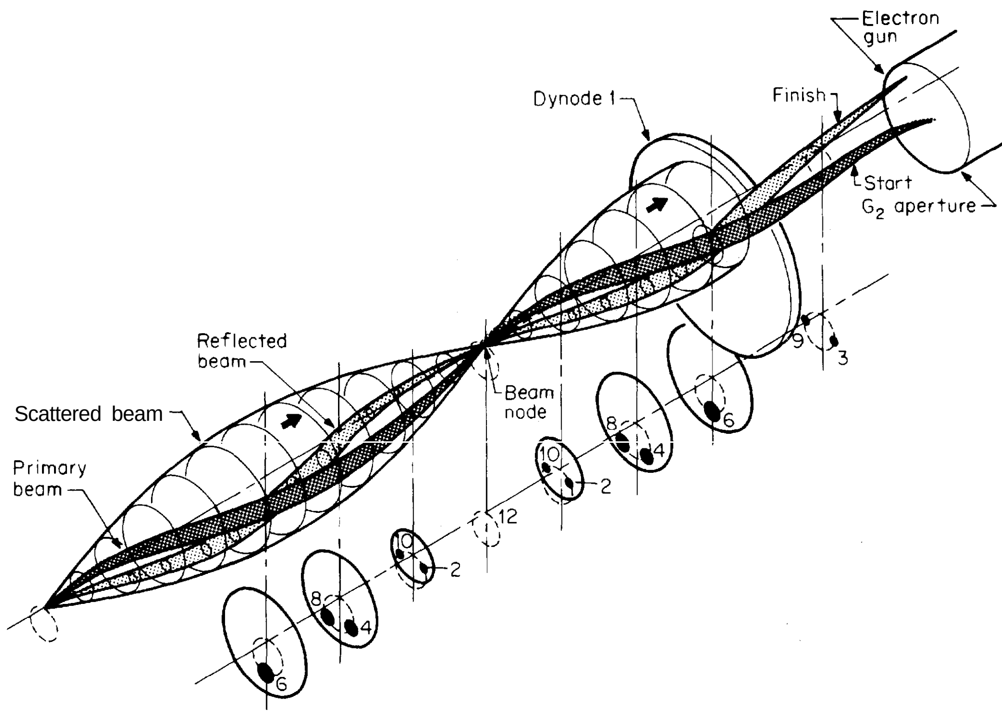

FIG. 11-29 Idealized trajectories of image-isocon electron beams. *(RCA Corp.)*

electrons in the gain-controlling buffer layer on the target structure (Fig. 11-33). Because of the high gain, the tubes are subject to rapid deterioration if they are overexposed, requiring fast-acting control and protection circuits in the camera.

The scanning section of the tube operates identically to a silicon-diode vidicon-type tube (see Sec. 11.1.2). Resolution in this type is limited by the diode structure of the target and reduced by the image section of the tube. The high gain at the target raises the signal level there by the gain factor. This greatly reduces the lag when operating at very low light levels. Recent versions of the SIT tube have reduced blooming because of an altered target structure, and target doping to prevent lateral migration of charge when

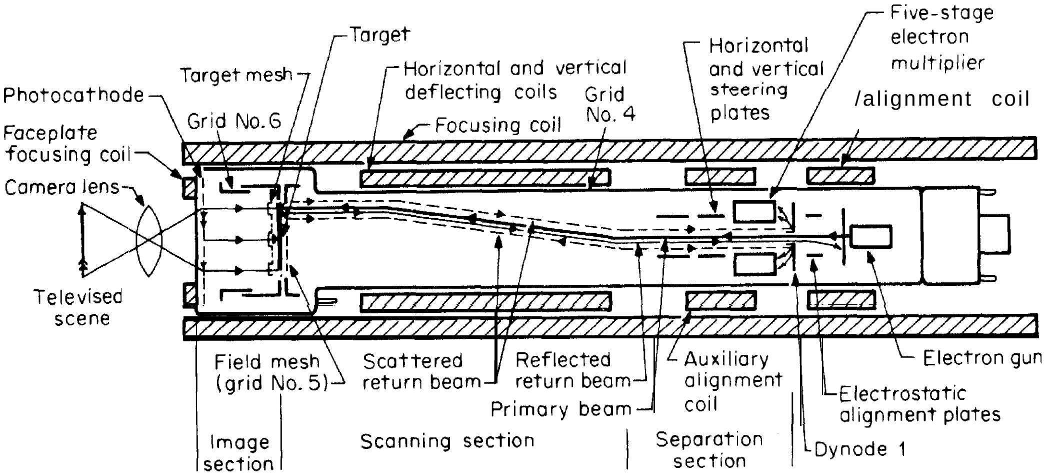

FIG. 11-30 Cross section of an image isocon and associated magnetic components. *(RCA Corp.)*

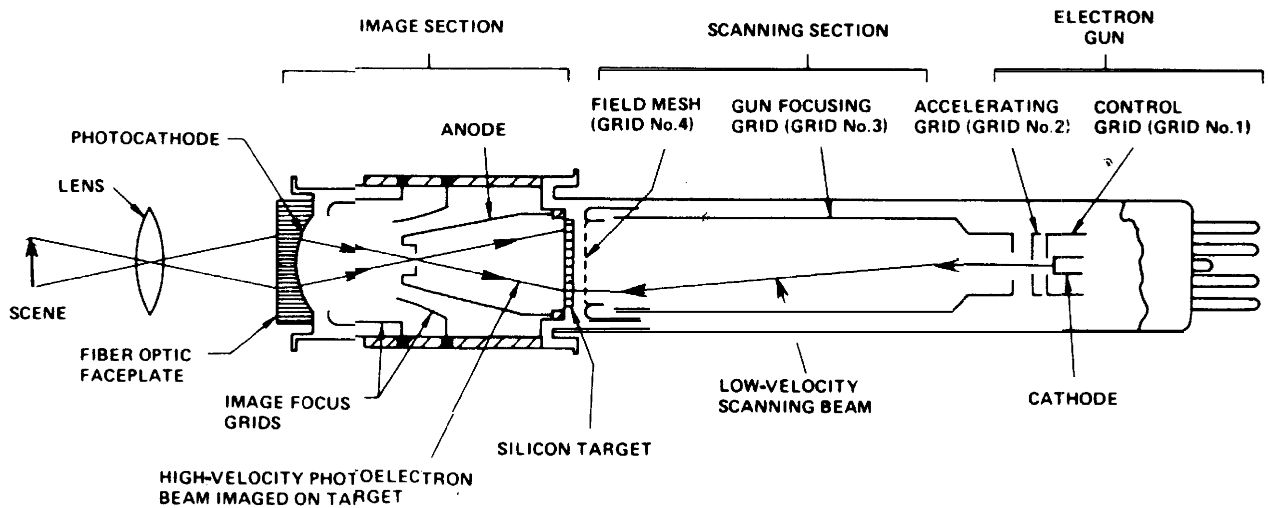

FIG. 11-31 Light enters the SIT tube through a fiber-optic faceplate, which transfers the flat-scene image onto the curved photocathode. The light then travels through the focusing grids and strikes the target, which is a matrix of over 1800 silicon diodes per inch (per 2.5 cm). The image is typically stored there and read out by the scanning beam every 1/30 s. *(RCA Corp. and SMPTE.)*

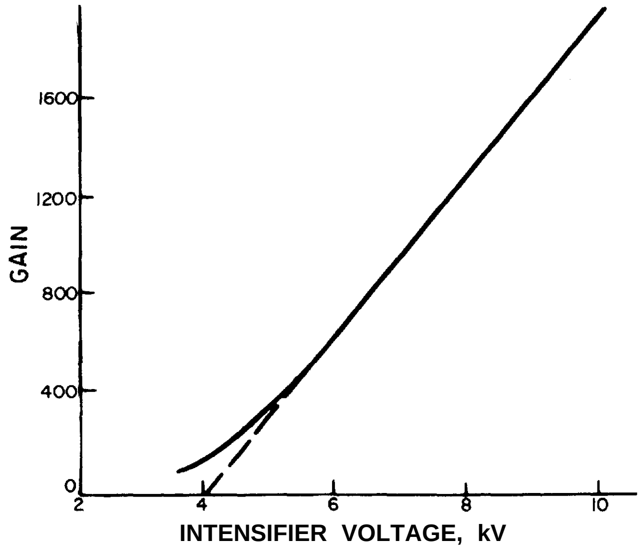

FIG. 11-32 Electron gain (solid line) is an essentially linear function of the intensifier voltage. An energy-absorbing buffer layer requires keeping the voltage above 3 kV, where the intensifier section performs best. Deviation from linearity (the dashed line) is caused by high-energy photoelectrons penetrating the buffer layer. *(RCA Corp. and SMPTE.)*

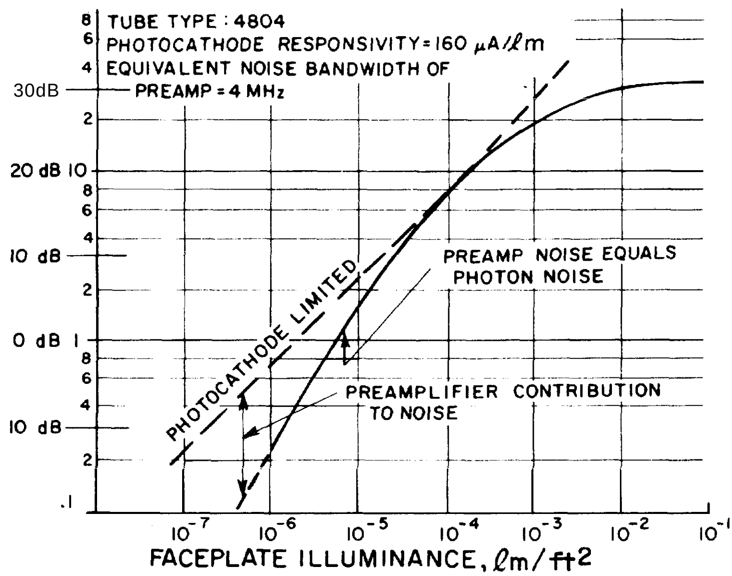

FIG. 11-33 Typical S/N characteristic for tube and camera. At higher illumination levels, intensifier voltage decreases to limit gain. This lowers the number of primary photoelectrons striking the target, so the S/N flattens out from the photocathode-limited line. *(RCA Corp.)*

the target becomes overloaded. The tube is generally made with a scanning section in the 25-mm diameter (l-in) vidicon size. Special designs with larger image formats are made when higher resolution is required.

11.4 VIDICON-TYPE CAMERA TUBES

The vidicon tube employing antimony trisulfide as the photoconductor was the first successful photoconductive television camera tube. The name *vidicon* has been adopted as a generic classification for photoconductive camera tubes. Various other photoconductive camera tubes that have been developed have been identified by trade names or the type of photoconductor that is utilized. All these tubes operate with a target readout signal and use low-velocity scanning with an electron beam. (See Sec. 11.2.6.)

The deflecting and focusing of the electron beam vary in many of these different tubes. Most tubes utilize magnetic focusing and magnetic deflection. Other types have electrostatic focus and magnetic deflection, or magnetic focus and electrostatic deflection, and a few use electrostatic focus and deflection.

All use an electron gun producing an electron beam, derived from a thermionic cathode, that emerges from a small aperture. Various versions of these guns have been designed to produce specific resolution values, low-impedance beams, or beams that can switch to a high-current erase mode during different portions of the scanning cycle.

The tubes are commonly 1/2 to 1% in (13 to 38 mm) in nominal diameter, although special 2- and 41/2-in-diameter (51- and 114-mm) tubes have been made for special high-resolution systems. These large tubes utilize the return-beam signal and have a built-in electron multiplier system for signal amplification.

All photoconductor-type vidicons, except the silicon diode tube, utilize a continuous-film structureless photoconductor deposited on a transparent signal electrode. The silicon diode photoconductor is a wafer of silicon on which an array of diodes with contact pads are fabricated.

11.4.1 ANTIMONY TRISULFIDE PHOTOCONDUCTOR. Antimony trisulfide photoconductors consist of alternating layers of porous and solid antimony trisulfide. The thickness of the material is approximately 1 to 2 μm. The operating target voltage can vary between a few volts and 100 V. Part of this variation in voltage is necessary to accommodate manufacturing variations. The rest of the range is used to control the sensitivity and/or dark current of the tube.

Dark current is fairly high on this type of tube. In a 25-mm-diameter tube it can vary between 1 and 2 nA at a low target voltage to 100 nA at a high target voltage. The dark current increases approximately as the cube of the target voltage, and the sensitivity varies as its square. At a high target voltage the tube is quite sensitive and laggy, and the dark current approaches the signal current level. At low target voltages the reverse takes place. Typical operating dark currents are in the 10- to 30-nA region. When tubes are set up to operate with similar dark currents, the sensitivities will be nearly identical. However the operating target voltages under these conditions will not necessarily be the same on all tubes. The adjustment of target voltage is therefore best established by setting for a desired value of dark current.

Dark current is a function of temperature. It approximately doubles for every 8” C increase in temperature. This is significant when operating in the high-sensitivity mode.

Antimony trisulfide is sensitive through the entire visible spectrum and has some sensitivity in the infrared spectrum. (See Fig. 11-34.) The signal output of antimony trisulfide tubes as a function of the light level is not linear. This signal varies at -0.65 power of the input light. (See Fig. 11-35.) This is a desirable feature since the progressive compression of higher signal currents partially compensates for the nonlinearity of a typical picture tube, which compresses blacks and stretches whites. Consequently the overall picture is brighter and has a more natural tonal rendition than that produced by a video signal which has a linear characteristic.

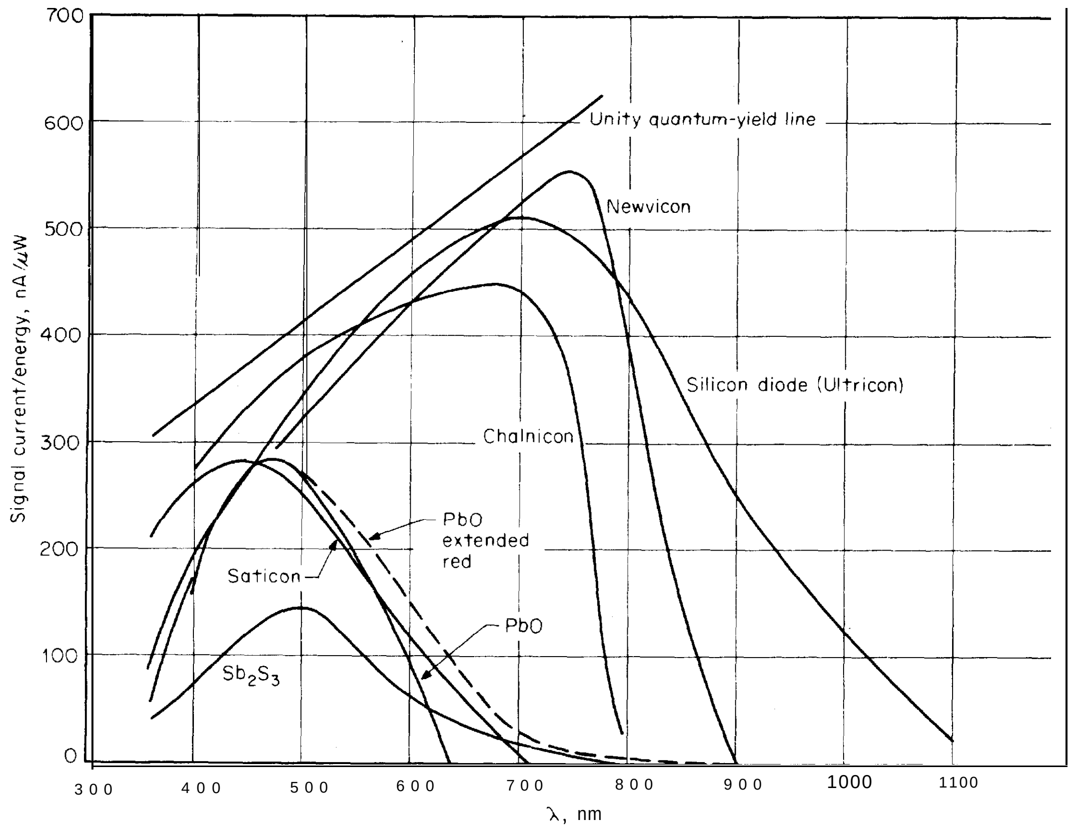

FIG. 11-34 Absolute spectral response curves of various camera tube photoconductors.

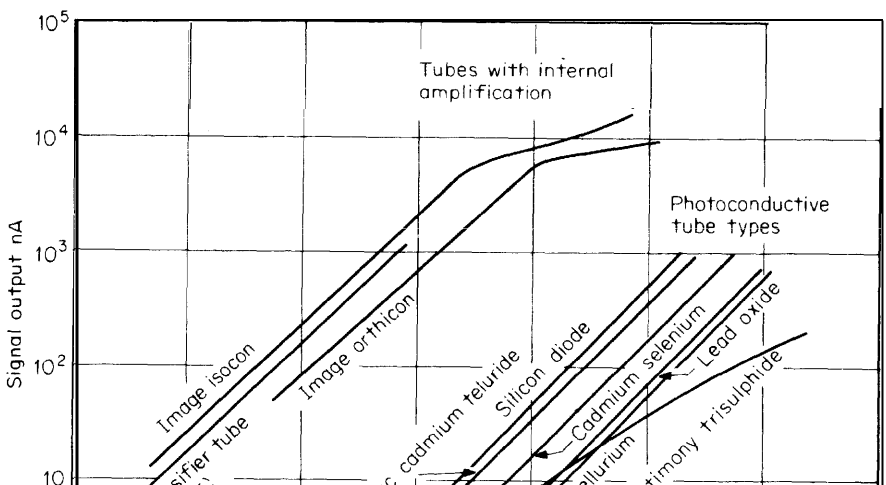

FIG. 11-35 Light-transfer characteristics of typical camera tubes.

Resolution of an antimony trisulfide photoconductor is not greatly degraded by the photoconductor, since it has high resistivity and is very thin. In the first place, scattered light cannot progress far laterally through this thin layer. Second, the photoconductor is dark in appearance. Therefore it absorbs most of the incident light and does not allow it to scatter laterally through the photoconductor, where it otherwise might contribute to lower resolution.

The low reflectance of the photoconductor also helps maintain the contrast of the image, since very little is reflected from the faceplate or from other portions of the optical system, which could scatter back onto the photoconductor.

Antimony trisulfide tubes are used primarily in industrial surveillance closed-circuit television systems and in telecine cameras in broadcast service. They are used where variable sensitivity of the tube is desired and where low cost is an objective. They are used in telecine cameras where the tubes can be operated with high light levels and at low dark current, which results in minimum lag.

11.4.2 LEAD OXIDE PHOTOCONDUCTOR. One of a group of photoconductors called *heterojunction* photoconductors, lead oxide photoconductor tubes, are variously called Plumbicons, Vistacons, Leddicons, or Hi-sensicons by different manufacturers. The lead oxide photoconductor is a porous vapor-grown microcrystalline layer of lead monoxide. The material is processed during the vapor growth so that it is approximately i-type; i.e., it has nearly equal hole and electron mobility. It is vapor-grown on an n-type transparent signal electrode (tin or indium oxide). The vacuum interface surface is treated so it has *p*-type conductivity. The cross section of this 10- to 20-μm-thick layer is illustrated in Fig. 11-36.

In operation, the *ni* and *ip* junctions are reverse biased by a positive voltage applied to the signal electrode and negative or zero volts established by the beam on the scanned surface, hence the categorization as a heterojunction structure. Reverse biasing greatly reduces the dark current, since holes from the signal plate are prevented from entering the photoconductor, and the p-type material on the scanned surface discourages accep-

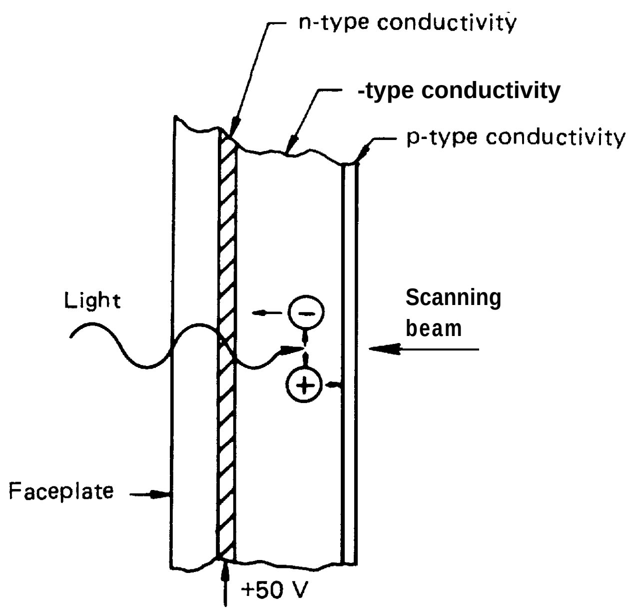

FIG. 11-36 Cross-sectional view of lead oxide photoconductor illustrating generation of output signal. *(RCA Corp.)*

tance of electrons from the scanning beam. Photons of light are absorbed throughout the bulk of the material, which has a band gap of 1.9 eV. Electron and hole-carrier pairs are generated from photons having more than this energy. Most of the applied target voltage appears across the bulk of this i-type layer. This field pulls electrons to the signal plate and holes to the scanned side, where they produce the positive-image charge pattern that is interrogated by the electron beam. Dark current from this photoconductor is less than 1 nA/cm^2 at the typical target voltage of 45 V. The 1.9-eV band gap is too wide to detect all visible light (700 to 650 nm). The spectral response is negligible from the 650- to 700-nm end of the visible spectrum. Red sensitivity and color fidelity suffer as a result, particularly in color cameras. Doped versions of this photoconductor, called extended red, produce additional red sensitivity, and extend the red sensitivity throughout the entire visible spectrum and into the near infrared (see Fig. 11-35).

The layer thickness is chosen as a compromise between sensitivity (particularly the red), lag, and resolution. Lead oxide does not highly absorb red and green light. Greater thickness increases the absorbed light and the red and green light sensitivity. The material is microcrystalline and therefore scatters light that is not yet absorbed. A thin surface has higher resolution than a thick layer, since scattered light cannot spread as far laterally. Blue light is absorbed strongly. Resolution of an image of blue light is not limited by the photoconductor thickness but is progressively degraded for light that is more weakly absorbed. Resolution for red light is lower than for green.

Because of the high reflection and dispersion and the low absorption of visible light, particularly in the red-green portion of the spectrum, severe halation can result, which reduces contrast and fidelity (see Fig. 11-37). A partial solution to this problem, used in most lead oxide tubes, is an antihalation glass faceplate button. This reduces halation within the tube. Light dispersed within the cone angle 2 reflects back into the optical system (Fig. 11-38). Here it can impair the contrast, as any other surface-reflecting element of the optical system will do.

Thicker layers have less storage capacitance. Since lag is proportional to the storage capacitance, thick layers produce the lowest lag. The doped extended-red version of the lead oxide photoconductor has higher red and green resolution than the undoped, because the doping material (generally sulfur) increases the absorption of the longer-wavelength light. The trade-off with this doping is higher lag and highlight image reception produced by trapping states in the material. These parameters are varied in different versions of these tubes to achieve the desired performance objectives.

The principal usage of lead oxide photoconductor tubes is in three-tube broadcast color cameras and in television intensifier systems used in conjunction with medical and industrial x-ray units.

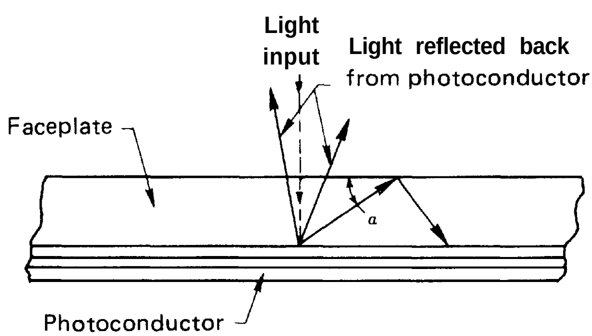

FIG. 11-37 Light paths without antihalation button. *Note:* Reflected light striking the faceplate at an angle less than the angle α (the total internal reflection angle) is reflected downward toward the photoconductor. *(RCA Corp.)*

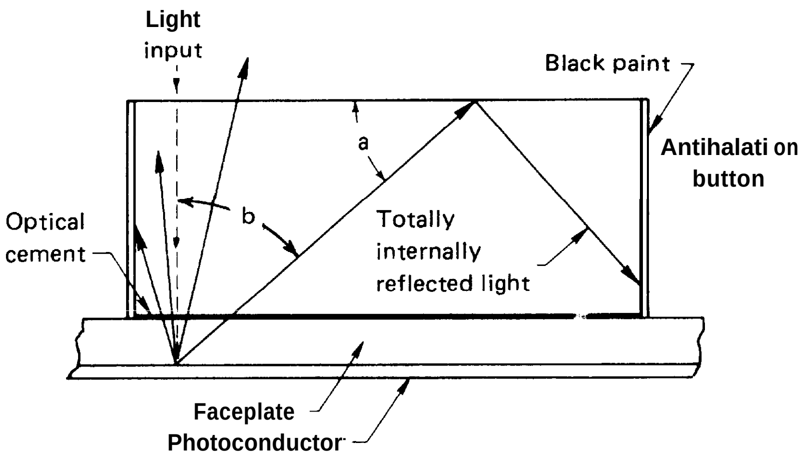

FIG. 11-38 Light paths with antihalation button. Note: Button thickness is designed so that all totally reflected light strikes the sides of the button and is absorbed by the black paint on the diffusing side of the glass. *(RCA Corp.)*

11.4.3 SELENIUM PHOTOCONDUCTOR. Used in Saticons, it is a glassy or amorphous selenium-based photoconductor of the heterojunction type. It incorporates arsenic to inhibit crystallization of the glassy material and tellurium to produce adequate red response. Its physical structure is illustrated in cross section in Fig. 1 l-39. The tellurium doping is located close to, but not on, the signal electrode. The antimony trisulfide coating on the scanned side acts primarily to reduce secondary emission of electrons from the scanning beam. The p-type conductivity discourages unwanted beam electrons from entering the photoconductor on that surface.

The electronic structure is illustrated in Fig. 11-40. The reverse-biased junction on the light input side prevents holes from entering the photoconductor from that side. The p-type nature of the bulk of the material and the thin antimony trisulfide prevent excess electrons from entering from the other side. As a consequence the dark current is less

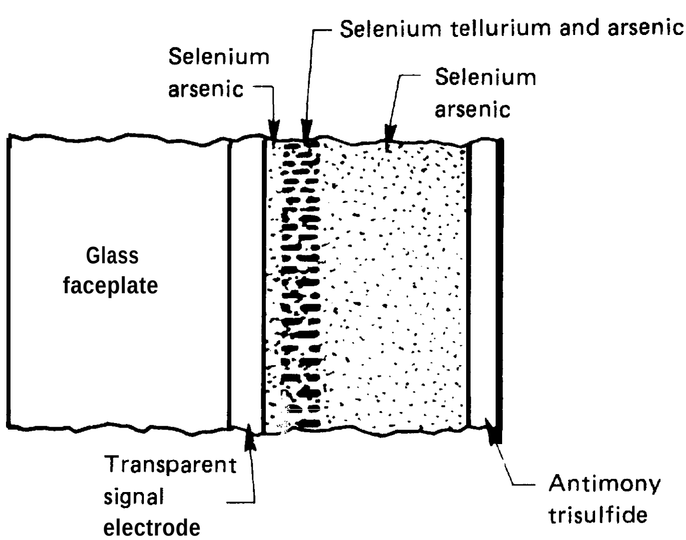

FIG. 11-39 Cross section of Saticon tube photoconductor and faceplate. *(RCA Corp. and SMPTE.)*

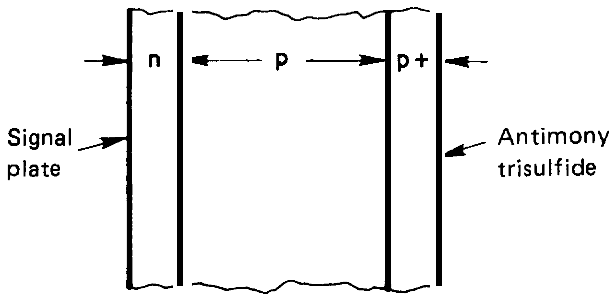

FIG. 11-40 Cross section of Saticon tube photoconductor showing electrical conductivity characteristics. *(RCA Corp. and SMPTE.)*

than 0.5 nA/cm^2. Selenium is highly absorptive for blue and green light. It has a band gap of 2.0 eV, which effectively limits sensitivity to wavelengths above 620 nm. Tellurium increases the absorption of red light to wavelengths as long as 700 nm, giving the photoconductor response throughout the visible spectrum. Photons of light are absorbed either in the selenium arsenic directly behind the signal plate or in the tellurium-doped region, Pairs of charge carriers are liberated in this region, and the holes are pulled through the p-type layer to the scanned side, where they generate a stored positive-image charge. Electrons having low mobility in the p-type material are able to traverse the short distance to the positive signal plate. The photoconductive conversion takes place in the first few dozen nanometers of this layer. The remainder of the layer acts primarily as a charge-transport layer. Because the material has high resistivity ($10^{13}\ \Omega \cdot cm$) and the field through the photoconductive layer is high (125 kV/cm), these charges travel without lateral diffusion, maintaining high resolution for all wavelengths of light. The material is glassy (noncrystalline). As a consequence light is not dispersed in the photoconductor. These factors preserve resolution and make the resolution of the photoconductor independent of the thickness or of the size of the useful photoconductive area of the tube. Because the photon conversion takes place in the front portion of the layer, sensitivity is independent of the photoconductor thickness. These factors make the photoconductor more versatile. Its parameters can be varied to produce changes in storage capacitance, to reduce lag, or be suitable in small-size tubes. Tubes with Saticon photoconductors have low flare. The high absorption of light by the photoconductor results in little light being dispersed or reflected back from the photoconductor. This helps to preserve picture contrast and tonal fidelity. It is particularly important when high-contrast images are encountered and in three-tube color cameras where brightness distortions become color distortions.

Advanced Saticon-type photoconductors designated types II and III are designed to reduce the memory of specular highlights and reduce any tendency for burn-in of stationary images.

Saticon tubes are used primarily in three-tube broadcast color cameras for studio, field production, and electronic news gathering, and in telecine cameras. Saticon tubes are also widely used in single-tube color cameras having color-filter systems of one form or another to perform the color separation functions, and in medical x-ray television systems.

11.4.4 SILICON-DIODE PHOTOCONDUCTIVE TARGET. The silicon-diode structure (Sec. 11.1.2) is a versatile photoconductor. It has the highest sensitivity of any camera tube photoconductor in the visible portion of the spectrum and extends its sensitivity well into the infrared region. Silicon-diode photoconductor tubes are made by various manufacturers under such names as Sivicor, Ultricor, Tivicor, and Silicon Vidicon. Dark current is in the range of 5 to 10 nA/cm^2. Resolution is limited by the diode structure, which usually has a square array of about 700 diodes per centimeter in either direction.

The recommended target voltage is in the range of 8 to 15 V. The storage capacitance of such a target is about 3500 pF/cm^2, making it one of the higher-capacitance photoconductors. This has an influence on low-level signal lag. The silicon diode target is also immune to image burn. In fact, it can be focused directly on the sun for short intervals with no permanent damage. With a 25-mm-diameter (l-in) tube, images of highlights tend to bloom when the target capacitance is completely discharged at a peak signal current in the range of a 1300-nA signal. Reduced blooming versions produced by variations in the structure of the target minimize this tendency in some tube models. The silicon target structure usually is self-supporting. It is positioned behind the faceplate rather than being deposited onto it.

The signal output, up to the saturation point, is linear; i.e., it has a gamma of 1.0. Special versions are made with targets that have enhanced infrared sensitivity to wavelengths of 1100 nm. Ultraviolet sensitivity to 330 nm can be obtained if a faceplate having good ultraviolet transmission is used.

Silicon diode tubes are most prominently utilized in closed-circuit monochrome systems where low-light sensitivity, infrared sensitivity, or resistance to highlight and other image burns is desired.

11.4.5 CADMIUM SELENIDE PHOTOCONDUCTOR. This photoconductor, used in the Chalnicon, consists of a microcrystalline layer of cadmium selenide (CdSe), an *n*-type photoconductor. Accordingly, it does not have blocking-type contact at the n-type signal plate, and dark current is not as low as in the heterojunction types of photoconductors. Versions of the Chalnicon are made by doping with cadmium telluride to increase the red and infrared sensitivity of the cadmium selenide. Cadmium selenide has a band gap of 1.7 eV, which limits the red response to wavelengths shorter than 730 nm, unless doped. Cadmium selenide layers are thin (1 μm) and consequently have high storage capacitance.

Latest versions have a composite structure with an added layer of arsenic selenide (As_2S_e,) in a porous-type structure on the scanned side. This increases the thickness and reduces the capacitance, thus reducing the lag. Tubes with this type of photoconductor are called Chalnicon-FR.

Sensitivity in the visible spectrum is very high and approaches unity quantum yield throughout most of the visible spectrum. The infrared-sensitive version has somewhat lower sensitivity in the visible spectrum but extends in sensitivity to beyond 800 nm (Fig. 11-35).

Target voltage for the Chalnicon tube varies between 20 and 50 V for different tubes and must be individually adjusted. Low target voltage produces excessive image retention. High target voltage produces spots and graininess. The required target voltage varies with temperature and is controlled by a temperature-sensitive control circuit. Dark current is in the 1- to 2-nA/cm^2 range for normal operating temperatures.

Lag and dark current are higher than in the selenium and lead oxide tubes, while the sensitivity is much higher. Resolution is about the same as in the Saticon. Some use is made of these tubes in three-tube color cameras, but their primary use is in surveillance-type cameras.

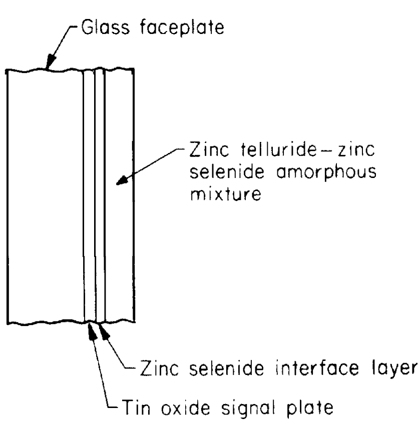

FIG. 11-41 Newvicon photoconductor cross-section schematic.

11.4.6 ZINC SELENIDE PHOTOCONDUCTOR. The Newvicon uses this heterojunction type of photoconductor. It consists of an amorphous or glassy interface-layer of zinc selenide, which is deposited on the transparent signal plate, and an additional amorphous layer consisting of a complex mixture of zinc cadmium and tellurium (Fig. 11-41). The zinc selenide layer provides the proper substrate for the photosensitive portion of the photoconductor, is n-type in conductivity, and is transparent to visible light. The zinc selenide-zinc telluride glossy layer is the light-sensitive portion of the photoconductor. It has p-type conductivity.

When the photoconductive target is reverse biased by application of a positive voltage to the signal plate, the dark current is in the order of 7 nA/cm2.

This dark current is higher than most other heterojunction camera tube photoconductors. The photoconductor operates best with a target voltage of 10 to 25 V across the layer, which is individually adjusted for each tube and for different temperatures to achieve a condition of minimum burn-in of images.

The Newvicon photoconductor is highly absorbing in the visible spectrum. As a consequence, it has very little reflectance. Flare caused by reflected light from the photoconductor is extremely low. Resolution of tubes using the Newvicon photoconductor is high. It is not primarily limited by the photoconductor because of its high optical absorbtion, high resistance to lateral leakage on the charge storage surface, and the negligible scattering of light in the thin, amorphous layer. It is also resistant to blooming or spreading of specular highlight images and has a low memory of specular highlights.

The Newvicon tubes are utilized primarily in surveillance, medical, and industrial x-ray intensification systems and other industrial-type cameras where high sensitivity is desired. The Newvicon photoconductor is also widely used in stripe color filter-type tubes for inexpensive single-tube VTR color cameras.

11.5 INTERFACE WITH THE CAMERA

The principal function of the camera is to operate the camera tube and process the video signal developed by it. The interface controls and connections between the tube and the camera are important and are discussed separately. Listed below, and illustrated in Fig. 11-42, they pertain primarily to photoconductor-type camera tubes:

Optical input
Dynamic focusing
Blanking the beam
Alignment coils
Video output
Deflection coils and deflection circuits
Magnetic shielding

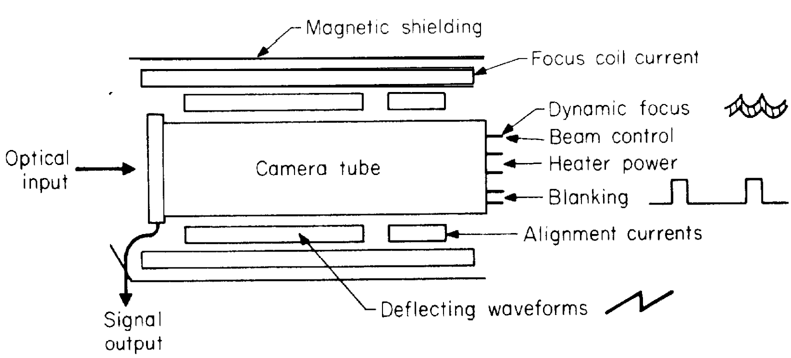

FIG. 11-42 Principal interface with the camera.

Table 11-1 Recommended Image Sizes of Various Photoconductive Camera Tubes

Nominal tube diameter		Image size (3 × 4 aspect ratio)					
		Width		Height		Diagonal	
mm	in	mm	in	mm	in	mm	in
38	1.5	20.32	0.80	15.24	0.60	25.4	1.0
25	1.0	12.7	0.50	9.5	0.375	15.9	0.625
18	0.66	8.8	0.346	6.6	0.260	11.0	0.432
13	0.5	6.5	0.256	4.9	0.192	8.13	0.320
30	1.2	16.9	0.667	12.3	0.500	21.1	0.834

11.5.1 OPTICAL INPUT. The image is focused on the photoconductive material deposited on the inside surface of the tube's faceplate. The exception is the silicon diode target tube, where the silicon wafer is generally mounted separately behind the faceplate. The faceplate is 1 to 3 mm (0.04 to 0.12 in) thick (specified in data sheets by each manufacturer) and has an index of refraction of approximately 1.5. The faceplate thickness and refractive index must be considered when designing the mechanical positioning of the tube relative to the lens and other portions of the optical system.

When the photoconductor reflects a substantial portion of the light incident on it, an antihalation button is needed. This reduces loss of contrast caused by light being reflected back to the photoconductor from the front surface of the glass. Figure 11-37 shows that when this diffused reflected light strikes the interface between faceplate and air at an angle less than α, all the light is reflected back on the photoconductor and produces an unwanted flare or halo around the highlight. The antihalation faceplate button (Fig. 11-38) moves this interface farther from the photoconductor so that the reflected light from the photoconductor is reflected back to the wall of the button, where a black coating absorbs it. When reflected light from the photoconductor strikes the faceplate-air interface at less than the angle α, a small percentage is reflected back from the interface and contributes to poor contrast.

Each class or size of camera tube utilizes a prescribed image size for optimum performance. These sizes are shown in Table 11-l. The *visible* area of the photoconductor is much larger than the values cited. When a larger area than specified is utilized, problems of geometric distortion, poor focus, nonuniform signal amplitude, and blemishes will probably be encountered as progressively more of the area is utilized. It is important to position the tube in the camera so that the longitudinal axis of the tube is precisely on the axis of the optical system. It is not good practice to utilize the additional sensitive area of the tube to accommodate for off-axis positioning of the tube in the camera.

11.5.2 OPERATING VOLTAGES. All voltages discussed in this section refer to the voltage between the cathode and the various other tube electrodes. G_4 and G_3 voltages in magnetically focused tubes control the transit time of electrons through the tube. They establish the transit time so as to bring electrons that start out from the gun with a radial component of velocity back to the axis of the beam after they have completed one 180° circle about the axial magnetic-focus lines of force. These electrodes therefore operate as a beam-focus control. A form of collimating lens is formed between the G_3 and G_4 electrodes. The shape of this lens is determined by the difference in voltage between the two electrodes. The purpose of the collimating lens is to assist in correcting the trajectory of the deflected electron beam so that the beam will land perpendicular to the faceplate. The strength and/or shape of this lens must be determined empirically for each focus-coil and deflection-coil combination. It is also a function of the axial positioning of the tube with respect to the coil. The strength and shape of this lens are controlled primarily by the ratio of the G_4 to G_3 voltage. G_4 (mesh) must *always* be higher (in voltage) than G_3. If not, any positive ions generated by the electron beam striking gas molecules in the tube will be accelerated to a diffuse spot on the photoconductor, causing permanent damage.

If the G_4 voltage is fixed more positive than the G_3, it creates a field that suppresses secondary electrons emitted from the mesh by the scanning beam. It prevents them from being trapped in orbits around the magnetic field lines. Trapped electrons can contribute a space charge that tends to disperse and defocus the scanning beam. Early vidicon tubes did not have separate mesh and wall electrodes. These were electrically and mechanically connected.

Beam Focus. Once the G_4/G_3 voltage ratio is established, the best way to achieve beam focus by varying the tube voltages is to vary the supply voltage to a fixed voltage divided circuit that always provides the proper voltage ratio. Currents drawn by the tube electrodes in normal operation are in the order of 10 μA, even when the beam is set to handle extreme highlights. Focus stability requires good stability of these voltages. A variation of 1 or 2 V can produce noticeable degradation of resolution.

The G_4, or mesh electrode, and to a lesser extent the focus electrodes, must be bypassed to the video input amplifier ground. This minimizes pickup of deflection transients or video signals that can be capacitatively coupled into the signal electrode through the capacitance of these electrodes to the target.

Resolution will be higher if the G_3 and G_4 are operated at high voltages. This also requires using higher magnetic focusing fields and focusing power. G_4 voltages below 300 V are generally unacceptable. Voltages of about 1000 V do not contribute much to improved resolution and can reduce tube life. High G_4 voltages do produce a stronger field between the G_4 mesh and the target and reduce beam bending (localized image distortion). This high field reduces the tendency for the scanning beam to be bent laterally as it approaches highly positive image charges on the scanned target or toward the positive unscanned areas around the edge of the scanned areas. In an *electrostatically focused tube* the G_5 and G_6 electrodes provide a similar function of beam collimation or deflected scanning beam trajectory correction. High G_6 voltages also reduce beam-bending effects at the target.

In electrostatically focused tubes, focus is achieved by an electrostatic lens or lenses placed midway in the electron optical system. Beam focus is achieved by varying the dc voltage in the appropriate focus electrodes, which in turn controls the strength of these lenses (see Fig. 11-43). Once the proper voltages for G_5 and G_6 and focus are established, and if the electrodes are all supplied by a voltage divided circuit from a common power supply, good beam focus is maintained over a wide variation in the high-voltage supply voltage.

G_2 voltage is used to provide an accelerating voltage for electrons from the cathodes of the tube. This voltage is not critical for beam focus, but it does determine the range of voltages for G_1 beam control and to a lesser extent determines the beam impedance and, hence, the lag of the tube. This voltage is usually fixed at the voltage recommended by the tube manufacturer. Currents into this electrode can be as high as 1 to 2 mA, although normally they are in the 200-μA region. The G_2 voltage is normally in the range of 300 v.

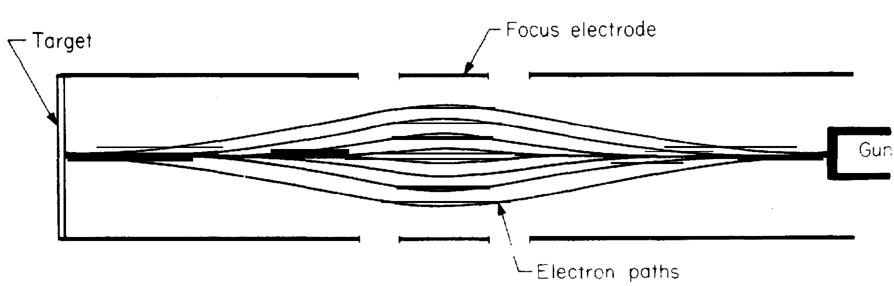

FIG. 11-43 Electrostatic focus.

G_1 voltage is used to control the amount of beam current. This is a tube setup control that must be adjusted for each tube in each camera. Sufficient negative voltage range (below the cathode voltage) should be provided in controls to allow the beam to be cut off completely. If the G_2 voltage is high, a more negative G_1 voltage range must be provided for proper beam control. Normally about − 100 V is provided for G_1 beam control.

Constant beam is often desired. One method of achieving this is to utilize a circuit that senses the current in the G_2 circuit and provides an automatic adjustment of the G_1 voltage to provide the proper constant G_2 current.

Optimum performance for lag and resolution can be obtained if the beam is set as low as possible to handle the signal level being developed. When specular highlights are encountered, high values of beam current are needed. Some cameras utilize circuitry that can "instantaneously" provide sufficient beam to handle the extra signal level. These circuits sample the video signal and feed a video-rate signal to the G_1 to automatically increase the beam current. These circuits are variously called CTS, ABO, DBC, or other acronyms that describe their function.

Target voltage is a positive dc level applied to the target in order to establish the proper electric field across the photoconductor. The scanned side of the photoconductor is established at the voltage of the thermionic cathode of the electron gun by the low-velocity scanning process of the electron beam. Target voltage is therefore the difference in voltage between the target electrode and the cathode. Each type of tube uses a different target voltage, ranging from 8 to 75 V.

If the target voltage is applied directly to the target, rather than to the cathode, a coupling capacitor of adequate size and voltage rating must be provided between the target and the video amplifier. This adds to the shunt capacitance of the tube output and degrades the signal-to-noise ratio. Many cameras connect the target directly to the amplifier at approximately zero *chassis* voltage and apply the target voltage by biasing the cathode negatively. The actual target voltage is the absolute voltage difference between these two electrodes. Target currents are in the 1- to 2-μA maximum range, and cathode currents are in the 1- to 2-mA maximum range.

The target voltage for most tubes is fixed for any one tube or tube design. The exception is the antimony trisulfide photoconductors. Sensitivity of this type varies drastically with target voltage. This factor is used to advantage in some cameras where sensitivity is adjusted either manually or automatically by varying the target voltage. A very high resistance in series with the target supply (when voltage is applied to the target) provides a degree of automatic sensitivity control to accommodate the light conditions of different scenes.

Heater voltage can be either alternating or direct current. The manufacturer's recommendation should be observed. Direct current is preferable, to avoid any possibility of ac hum getting into the video signal. Voltages higher or lower than normal will shorten tube life. Regulation of ± 5 percent is adequate. The voltage rating between heater and cathode should be observed, particularly when a dc voltage is applied to the cathode to achieve the proper target voltage.

11.5.3 DYNAMIC FOCUSING. Dynamic focusing is the process of correcting the focus of the beam to accommodate defocusing caused by deflection of the beam. The deflected beam travels a longer distance than the undeflected beam in its trip from the cathode to the target. Hence, it comes to focus slightly behind the target. Focus can be restored by applying an ac voltage wave form to the G_3 focus electrode. This voltage is parabolic in shape and increases in voltage as the beam is deflected on each side of center. Both vertically and horizontally synchronous parabolic waveforms are needed to produce proper focus uniformity. The peak-to-peak voltage required for focus modulation is in the range of 10 to 20 V.

11.5.4 BEAM BLANKING. It is necessary to prevent the beam from landing on the target during both vertical and horizontal retrace. Blanking prevents erasure of the stored charge during retrace and also provides a black-level reference signal during each retrace interval. Blanking can be accomplished by applying a negative blanking signal to the G_1 sufficient to cut off the beam. An alternative is to apply a positive blanking signal to the cathode sufficient to raise its voltage above the few volts potential of the image charges on the target. The blanking voltage pulse should be as long as the retrace time of the deflecting circuit and narrower than the final picture blanking. A spurious signal which is developed at the very edge of the scan, as defined by the start and stop of the camera tube blanking pulses, should be blanked off on both sides and top and bottom from the final video signal by the wider system blanking pulse. To accomplish this vertically, it is desirable to generate a vertical system blanking pulse that starts several scan lines before the camera vertical retrace and the camera vertical-blanking pulse. A few microseconds delay of the video signal in the video amplifiers usually provides this guard time at the right side of the picture in the horizontal direction. (See Fig. 11-44.)

When the beam is prevented from landing on the target during retrace, the signal output is zero. The signal level during this retrace interval can be used to provide an absolute black-level signal reference and can be the signal level used for clamping or dc restoration purposes.

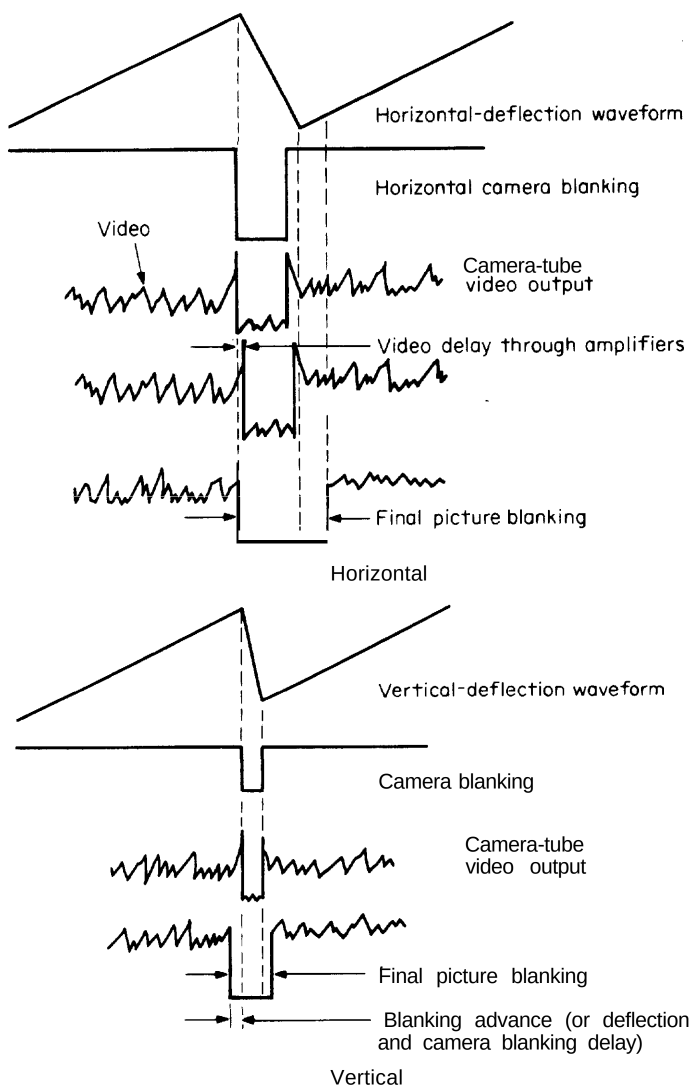

FIG. 11-44 Blanking and deflection waveform timing.

When both blanking and *target* voltage are applied to the cathode of a tube, the target voltage is the absolute dc voltage of the cathode during the active scan time with respect to the target.

11.5.5 BEAM TRAJECTORY CONTROL

Alignment Coils. Alignment coils are usually employed to correct the beam trajectory so that the undeflected beam lands perpendicular to the target in the center of the picture. One symptom of nonperpendicularity is translation of the center of the image, as focus is varied. A useful technique to properly adjust alignment is to rock the beam focus manually or electrically. This can be done by applying a frame-scan rate square wave to G_3. The alignment coil current (or field) is then adjusted so that the image rotates about the center of the picture.

Pairs of orthogonal alignment coils (or adjustable magnets) are positioned over G_2 of the tube and are used to provide the magnetic field. The consequences of improper alignment can be poor lag, nonuniform signal output, nonuniform focus, and geometric distortion or bowing of lines across the picture.

Focus coils that have a uniform field strength extending from the target to the G_2 aperture usually do not require alignment coils. Shorter focus-coil systems suffer in performance if alignment is not provided.

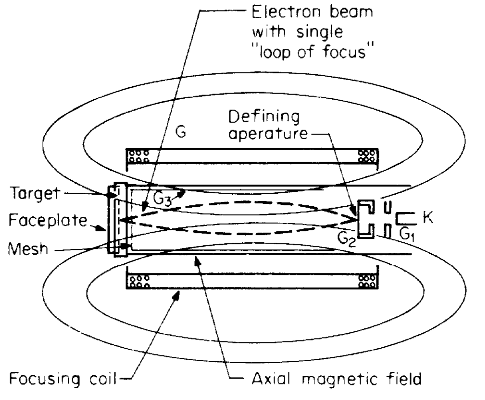

FIG. 11-45 Magnetically **focused vidicon, tube** system. ***(RCA Corp. and SMPTE.)***

Magnetic-Focusing Coils. Magnetic-focusing coils are used on many vidicon and other types of camera tubes to provide beam focus. The focusing coil is a solenoid surrounding the tube producing a reasonably uniform axial focus field (Fig. 1 l-45). The electrons emitted from the gun that move parallel to the focus field are unaffected by it. Electrons with a radial component of velocity cross the magnetic field lines, complete a circle, and arrive back at the same magnetic field line at a time proportional to the magnetic field

$$T = \frac{3.56 \times 10^{-7}}{B} \qquad (11\text{-}4)$$

where B = magnetic field in gauss. Focus of the beam is achieved by adjusting the voltages on the tube electrodes (and hence the beam velocity), so that the transit time of the beam through the tube is equal to the time of rotation of the radial directed electrons (Figs. 11-46 and 1 l-47). In most vidicon camera tube systems a single loop of focus is utilized. Increasing the magnetic field by a factor of 2, or decreasing the accelerating

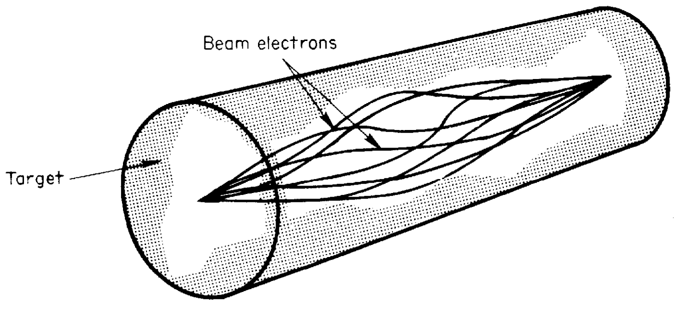

FIG. 11-46 Magnetic focusing.

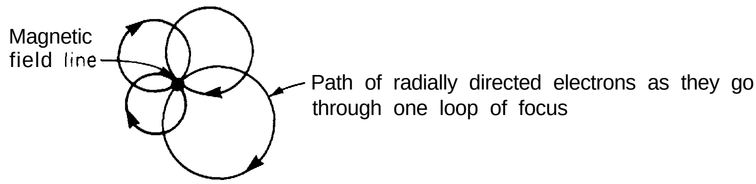

FIG. 11-47 Axial view of the path followed by beam electrons having a radial component of velocity.

electron field by a factor of 4, will result in the beam going through two loops of focus instead of one. This method of operation generally increases the focus error caused by electrons having different thermal velocities. Multiple focus loops are used in some specialized camera tube systems, where this design is useful in obtaining better collimation of the beam at the target. By judicious use of multiple loops of focus, aberrations caused by the deflection process can be minimized or canceled.

Care must be taken in the design of both the focusing and deflecting coils so that the focusing coil is not excited by the deflecting coils at a resonant harmonic frequency of the scanning frequencies. If this happens, localized focusing and geometric distortion will occur.

The shape of the focusing-coil field can influence the system resolution and resolution uniformity. A strong magnetic field over the target and a weak field over the electron gun will demagnify the beam and improve the center resolution, usually at the expense of corner resolution. Some of this degraded corner resolution can be recovered by the use of focus modulation voltage waveforms applied to the focusing electrodes of the tube.

The shape of the magnetic field at the front of the tube has an influence on the collimation of the beam. The deflected beam has both a radial and a tangential component of velocity as the beam approaches the faceplate (Fig. 11-48). The collimating lens formed by the G_3 and G_4 can correct for the radial component of velocity. A flared **mag-**

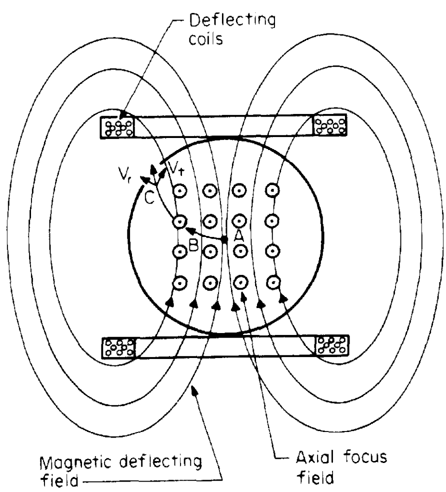

FIG. 11-48 Front view of deflected beam trajectory in a magnetically focused, magnetically deflected vidicon showing the radial (v_r) and tangential (v_t) component of beam velocity as it approaches the target. ***(RCA Corp. and SMPTE.)***

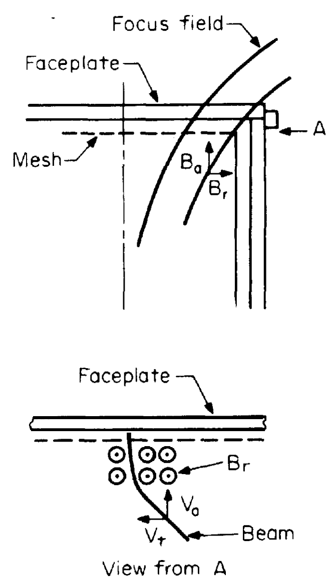

FIG. 11-49 v_r compensation using radial component of magnetic-focusing field. ***(RCA Corp. and SMPTE.)***

netic focus field (having radial components) can compensate for tangential components of beam velocity and bend the beam so that it approaches the target perpendicularly (Fig. 11-49). For this reason the axial position of the focusing coil with respect to the deflecting coil and the tube is critical It must be carefully determined and properly maintained for any tube, focusing-coil, and deflecting-coil system.

Focus current must be regulated very accurately to maintain focus, more accurately than the voltage on the tube electrode. The length of the focus *loop* in a tube has the following relationship to the voltages and focusing field

$$L = K\frac{\sqrt{V}}{H}$$

where L = loop length
V = voltage on focusing electrode
H = magnetic field, G

11.56 VIDEO OUTPUT. Video output is taken from the target. In most tubes contact is made through the target ring. This ring serves the dual function of providing the seal between the faceplate and the bulb and providing electrical contact through the tube envelope to the target signal electrode. The shunt capacitance of this circuit to ground (including the amplifier input and wiring capacitance) controls the signal-to-noise ratio of the video signal

$$\frac{\mathrm{S}}{\mathrm{N}} = K_1 \frac{i_s}{\sqrt{\Delta f + K_2\,(AF)^3C^2}} \tag{11-5}$$

where i_s = peak signal output
f = bandwidth, Hz
C = total shunt capacitance of tube and first amplifier stage
S/N = peak signal to rms noise

Negligible noise is produced by the signal current from the tube itself compared with the noise in the input amplifier. In the signal current rms noise is $\sqrt{2ei\,\Delta f}$. Δf is modified by tube resolution, since the output signal does not have-a flat frequency response.

The output impedance of the target is extremely high and can be considered as a constant-current generator. The shunt capacitance to ground can be as low as 2 pF for the low-output capacitance versions, and as high as 12 pF for the larger tubes. These values are increased when the tube is mounted in a coil assembly.

The high-frequency components of the signal are shunted to ground through the shunt capacitance of the target and amplifier input circuit. The signal can be processed in an amplifier to restore the system frequency response drop-off and phase shift produced by the progressive loss of high-frequency information caused by the shunt capacitance. When this is done, the flat-spectrum noise of the input stage noise is boosted in the high frequencies (above a few hundred kilohertz) and produces a signal dominated by high-frequency noise. The spectrum of this noise is called a *triangular-noise spectrum,* continuously rising to the frequency cutoff of the amplifier.

Where high signal-to-noise is a major factor in camera performance, low-output capacitance tubes are used to reduce the shunt capacitance of the target circuit. Figure 11-50 illustrates the components of capacitance of a conventional tube. Figure 11-51 illustrates the structure and the shunt-capacitance factors of this design.

The target electrode is a good antenna for high frequencies, and, therefore, must be inside a well-shielded enclosure that is bypassed to the input ground of the first amplifier stage. This enclosure includes the internal shielding of the focusing- and deflecting-coil system and the G_4 (mesh) electrode of the camera tube. This electrode must be well bypassed to the same ground system as the remainder of the target-shielding enclosure. Deflecting-coil shield grounds should not run through this same circuit.

Signal currents range from several nanoamperes to 1 or 2 μA. For broadcast television, and other reasonably critical systems, peak signal currents of 150 to 600 nA are utilized for normal-sensitivity operation. For high-sensitivity operation in limited light condi-

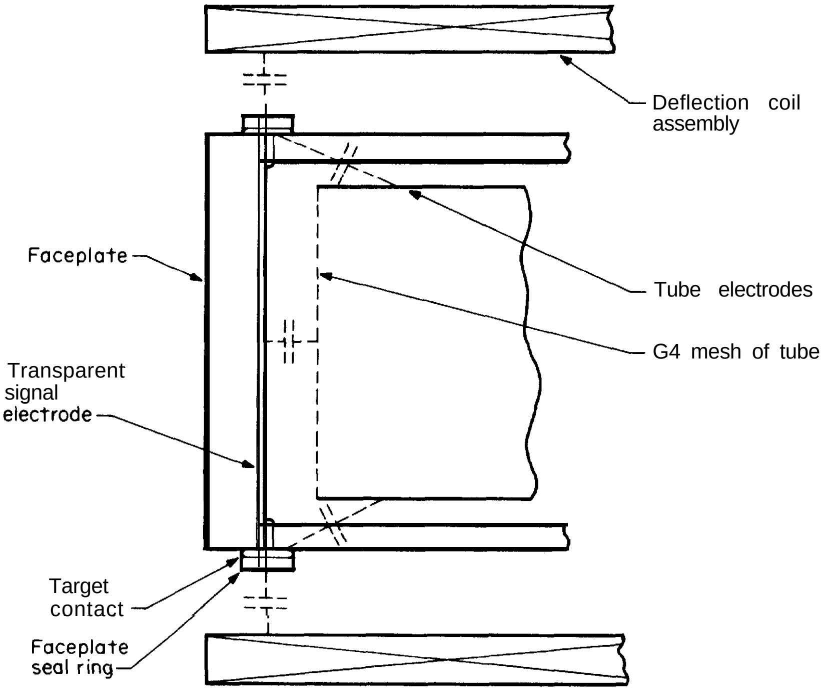

FIG. 11-50 Output-capacitance sources of standard tube.

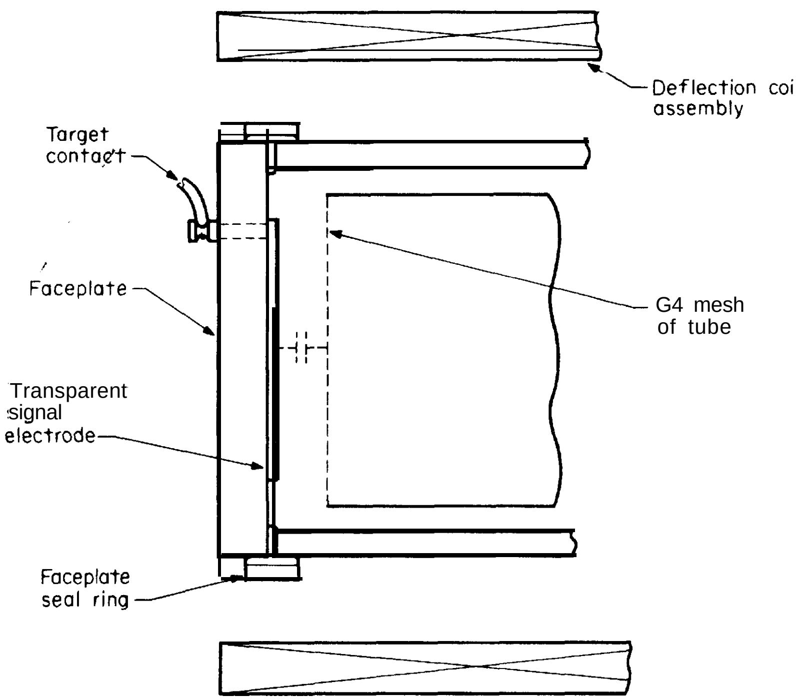

FIG. 11-51 Output-capacitance sources of low-capacitance tube.

tions, signal currents of one-tenth these values are often utilized. The polarity of the signal highlights is negative.

The signal during the interval of retrace across the target is zero. This provides a reference level on which black-level sensing or dc restoration can be performed.

11.5.7 DEFLECTING COILS AND CIRCUITS. Two sets of magnetic deflecting coils produce a pair of transverse deflecting fields. Both of these sets of coils produce fields that have the same position along the axis of the tube, which implies that coils are usually concentric. Each coil of a pair is wrapped around the tube nearly 180° (Fig. 11-52). Impedances (inductance) are kept low (about 1 μH) for the horizontal deflecting coil to reduce the peak voltage during retrace and to keep the resonant frequency high so that the retrace time (determined by the resonant frequency) is short.

The coils are shielded from the tube electrodes by internal Faraday shields that do not buck the magnetic deflecting fields, but instead reduce the electrostatic pickup that can be coupled from the coils to the tube electrodes and, in turn, into the signal plate of the target.

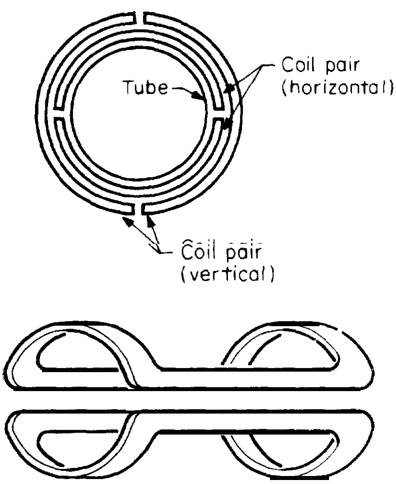

FIG. 11-52 Traditional shape of a pair of deflecting coils.

In electrostatically deflected tubes, the direction of deflection is perpendicular to the magnetic-field lines. In magnetic-focus tubes, the beam is initially deflected perpendicular to the magnetic field of the coils. This causes it to traverse the focusing field, which in turn causes it to take a spiral path. Thus, the actual deflection path at the target occurs nearly parallel to the deflection coil field.

The deflecting-current waveform is essentially a linear sawtooth for both vertical and horizontal deflection coils. The G_3 or focus electrodes are made of high-resistance material to reduce the loading on the deflecting coil and to minimize induced circulation currents which buck the deflection field.

The unavoidable bucking field produces some nonlinearity of scan, particularly at the horizontal-deflection frequency. This necessitates putting slight compensating distortions in the scanning-current waveforms to achieve good linearity of scan. Tubes made by different manufacturers often require individual adjustment of horizontal linearity to compensate for the loading or eddy-current bucking effects.

Timing of waveforms for deflecting and blanking is important. The typical timing is shown in Fig. 11-44.

11.58 MAGNETIC SHIELDING. Magnetic shielding is generally required to prevent deflection, or misaligning, of the beams by the earth's magnetic field and other stray magnetic fields. Ideally, the tube and deflection coils should be completely enclosed in magnetic shielding. An input port must, of course, be provided for the optical input. Adequate magnetic shielding is particularly important for color cameras where external magnetic fields can produce misregistration of images.

11.5.9 ANTI-COMET-TAIL TUBE. Versions of lead oxide tubes called ACT or HOP by their manufacturers are designed to erase signals generated by excessive highlights during the retrace interval of each horizontal line. This erasure minimizes the comet *tail* produced by brightly moving objects going across the field of view. The gun is designed so that pulsing an extra electrode between the control grid and the small beam-defining aperture in the gun will focus the beam crossover directly on this aperture. As a result,

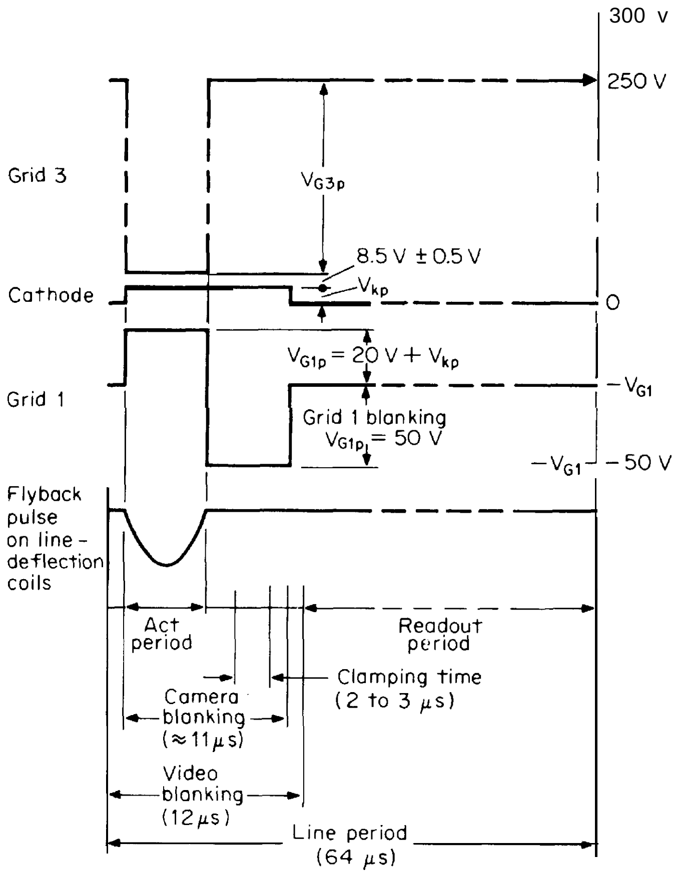

FIG. 11-53 Voltage and pulse timing for ACT- or HOP-type guns. *(© 1983 Philips Export B. V.)*

a very high beam current can be produced during this pulse interval which takes place during horizontal scan retrace. During this interval, the cathode is pulsed several volts more positive than during the scan readout interval. Consequently, it will land on the target only in places where the image charge exceeds this additional pulse voltage. This pulse voltage is adjusted in operation so that the excessive beam erases charge signals which occur just above the normal highlight signal level.

The typical pulse voltages and timing required to operate this type of tube are shown in Fig. 11-53. In this case, the voltage on the extra gun electrode controls the position of the beam crossover. The G_1 voltage is pulsed positively during the beam retrace interval to produce a very high beam current. It is cut off during the remainder of the blanking cycle to produce a video signal black-level reference for video clamping purposes. The camera video amplifier used with these tubes must be capable of handling a peak signal current at least 300 times normal highlight level without overload to accommodate the large signal pulse occurring during retrace. Tube life is maximized if this circuitry is activated and utilized only when specular highlights occur in the picture.

11.6 CAMERA TUBE PERFORMANCE CHARACTERISTICS

Sensitivity, resolution, and lag are the three most important camera tube performance characteristics.

11.6.1 SENSITIVITY AND OUTPUT. Photoconductive-tube sensitivity is straightforward. Relative sensitivity can be determined by inspection of the absolute spectral response curves of the various photoconductors (Fig. 11-34). None of these photoconductors produces greater than unity quantum yield, i.e., more than one electron of signal current per incident photon of light. In broad photographic terms, the photoconductors on 25-mm-diameter (1-in) tubes used for broadcast television service have a sensitivity equivalent to film that has an ISO exposure index (EI) of 300 when used with tungsten illumination. Sensitivity is lower when utilized in a color camera that splits the light three ways to three different tubes, or when other color filters are introduced.

In a camera tube, unlike film, the equivalent ISO sensitivity changes as a function of the image size. If a smaller image size is used, fewer lumens of light will fall on the image for the same scene illumination and lens opening. Therefore, a lower signal output current, in direct proportion to the reduction of the scanned area, will result. A lower lens *f*-number, or larger aperture, must be utilized to increase the signal level to the expected level. At first glance it might seem that the smaller tubes are less sensitive. This is not necessarily the case, because of the geometry of the optics. When the optics are analyzed and a comparison is made on the basis of the same *angle of view* and the same *depth of focus* for the small and for the large image format lens, it turns out that the smaller image format lens will have the same diameter of opening as the large one; i.e., it collects the same number of lumens of light. The *f*-number of the small image format lens will be smaller, but the system performance factors, depth of focus, angle of view, and signal output from the tubes will be identical to those of the large image format system.

Light-transfer characteristics (Fig. 11-35) are more useful in relating scene illumination and signal output from a camera tube. By industry convention, light-sensitive devices are evaluated with tungsten illumination with a color temperature of 2856 K. This is typical of normal tungsten-bulb illumination. (Studio lighting is usually a higher color temperature of 3200 K, and sunlight is ~ 5900 K.)

Scene illumination and the illumination of the faceplate of a tube in a simple optical system are related in the following manner

$$I_s = 4I_{pc}F^2/TR \tag{11-6}$$

where I_{pc} = illumination of photo surface
F = lens *f*-number
T = lens transmission
R = scene highlight reflectance

T of a lens is typically 0.8. The simplified equation can be expressed as

$$I_{pc} = I_sR/5F^2 \tag{11-7}$$

Signal Output. From the light transfer characteristics, a signal output can be determined if the faceplate illumination I_{pc} is known. Light transfer characteristics are traditionally published as dc signal output measurements made with uniform illumination. Peak-signal currents will be higher because part of the time the scanning beam is blanked off, and all the signal is developed during the active scan time. Peak-signal output will be the indicated signal output from the light transfer characteristics divided by the percentage of unblanked scanning time

$$I_s = \frac{I_s \text{ indicated}}{\text{\% unblanked camera scan time}} \tag{11-8}$$

Equivalent ISO Exposure Index. Camera tube sensitivity can be related to film exposure indexes (ISO ratings) by the use of Fig. 11-54. In the television system, the *exposure time* is fixed by the television scan rate. A comparison of photographic to television reproduction of moving images reproduced by a low-lag camera tube shows that the most realistic time interval for a television signal corresponds closely to a photographic exposure of 1/60 s. Consequently, if the tube specification recommends a certain faceplate illumination in footcandles, the television camera will require the same lens

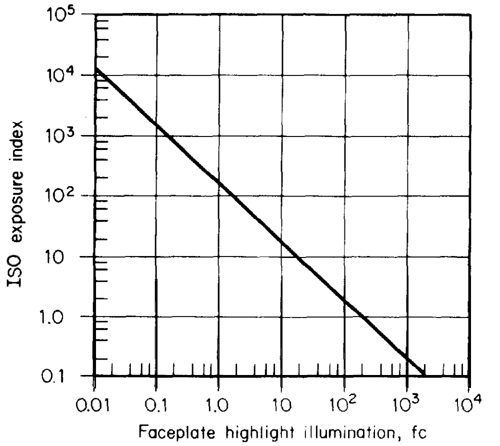

FIG. 1 l-54 IS0 exposure index values vs. faceplate illumination for camera tubes operated on United States broadcast scanning standards (equiv. shutter speed *1/60 s). (RCA Corp. and SMPTE.)*

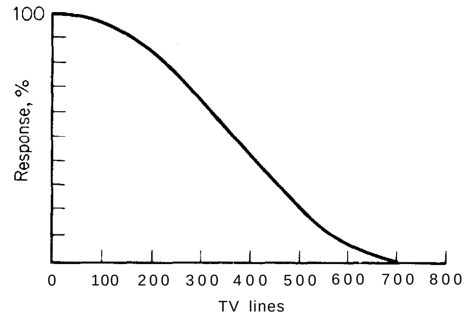

FIG. 11-55 Typical camera tube amplitude response curve.

opening and light level as a photographic camera operating at a shutter speed of 1/60 s would with film of the IS0 rating determined by Fig. 11-54.

11.6.2 RESOLUTION. Resolution is the ability of a tube to faithfully reproduce fine-detail information and transitions between dark and light parts of an image.

The use of limiting resolution as a measure of a tube's resolution fidelity is usually subjective and therefore given to error. However, an even more compelling reason for abandoning the process of using limiting resolution for evaluation of a camera tube is the fact that the adjustment of beam and lens focus for maximum limiting resolution is different from the point-of-focus adjustment required for maximum subjective sharpness of the television picture.

Consequently, resolution of camera tubes is commonly expressed as amplitude response or depth of modulation. The data are presented either as a number defining the response of the tube to a square-wave test pattern consisting of black and white bars of a certain size, or as a curve showing the response from coarse to very fine test-bar patterns (Fig. 11-55). The size of the test pattern bars is expressed in a television line number, which is the number of black and white bars of equal width that will occupy the vertical dimension of the television picture. Actual response curves to a square-wave pattern are often referred to as the *contrast transfer function* (CTF). This can be contrasted to lens and film technology which utilizes test patterns calibrated in line pairs (one black and one white) per unit length across the actual image. The response data usually are converted to *modulation transfer function* (MTF), which is the response to a sine-wave test pattern. The resolution performance of a system can be predicted from the product of the MTF of each component." For this purpose it is necessary to convert camera tube CTF data to MTF data, using the following relationship

$$\mathrm{MTF}_n = \frac{\pi}{4}\left(\mathrm{CTF}_n + \frac{\mathrm{CTF}_{3n}}{3} - \frac{\mathrm{CTF}_{5n}}{5} + \frac{\mathrm{CTF}_{7n}}{7} - \cdots\right) \qquad (11\text{-}9)$$

MTF,, = MTF at television line number *n* and CTF, = CTF at the corresponding television line number. MTF data for lenses must be converted to television lines per picture height of the image size used in the particular case.

In television technology, several shortcuts are often used to express camera tube resolution. The most common is the response at 400 television lines. This represents a frequency of 5 MHz for vertically oriented bars in both 525- and 625-line systems, This value is used because it corresponds roughly to the bandwidth of the television channel.

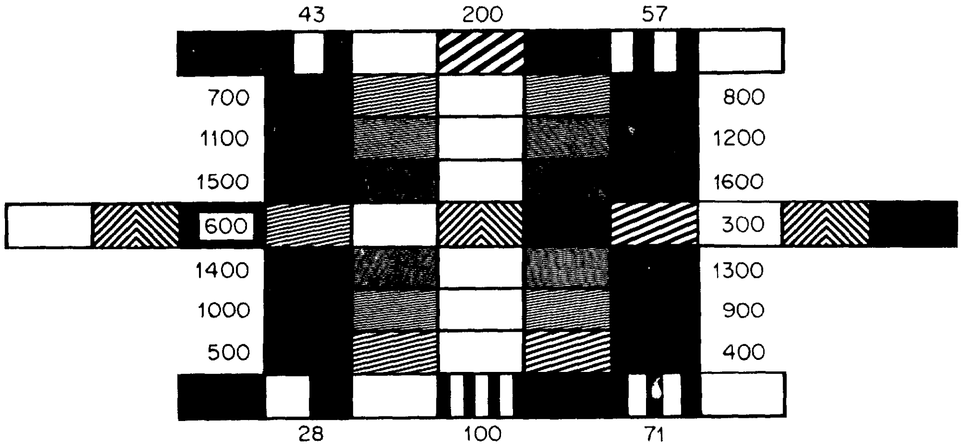

FIG. 11-56 Center section of P200 test chart. *(RCA Corp. and SMPTE.)*

It represents the point where the response of camera tubes is usually dropping off rapidly and is therefore a sensitive single-number comparision figure. The video frequency of any vertically oriented pattern in 525- and 625-MHz line systems can be determined from the relationship 1 MHz = 80 television lines.

Resolution Measurement Methods. Tube resolution cannot be measured independently of the deflecting- and focusing-coil systems, but must be measured in the coils in an operating camera, whose design can influence the resolution of the tube.

One method of determining resolution involves measurement (by means of an oscilloscope) of the response of a camera tube to a line pattern calibrated in television lines per picture height. However, this measurement should be made with the aid of a test method that is independent of observer judgment and test equipment variation. For vertically oriented test bars the measurements vary with the frequency response of the amplifier, since finer-pitched test lines produce higher-frequency signals. The bandwidth must be significantly greater than the frequency being measured, so that sufficient harmonics of the fundamental frequency can be present to reproduce the square-wave signal.

The technique of testing a high-impedance video preamplifier for flat response is a difficult one, and one subject to many pitfalls that produce errors. As a result, differences in measurement by factors of 2 to 1 can be experienced between test equipments in various laboratories. One way to avoid frequency-response errors is to use a special test pattern designed to measure resolution data independent of the amplifier frequency response. One test pattern, the RCA P200, shown in Fig. 11-56, has been adopted by several television organizations and laboratories for evaluating camera tube resolution. This test pattern is designed with line patterns that are rotated from their usual vertical orientation so that the beam traverses them at a slower rate (Fig. 11-57). The signal output from these line patterns is, then, produced at a lower frequency. Since the frequency of the video signal varies as the sine of the angle from the horizontal, the maximum and minimum signal outputs, as the beam traverses the light and dark bars of the test-pattern image, are essentially independent of the direction of scan across the test pattern. This fact allows a design of test patterns that produces two important results: First, the bandwidth of the required video amplifier system is reduced; second, each group of lines of the bar pattern can be inclined at an angle such that each set of bars representing different television line numbers produces the same fundamental video frequency. This latter feature eliminates the amplifier frequency response as a factor in the measurements.

In the center of the pattern is a chevron-shaped pattern of 400 television line bars. The lines are oriented 90° from one another, and both sets of lines are oriented 45° from the vertical. This portion of the pattern is utilized when focusing the beam, and to detect

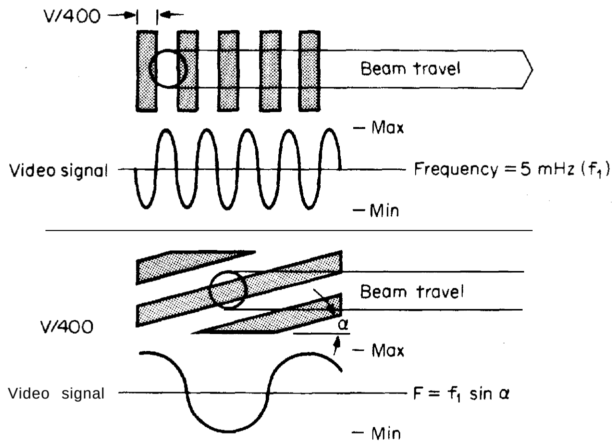

FIG. 1 1-57 The principles of the P200 slant-line test chart showing how the measurements can be made at a lower video frequency and how all line number measurements above a low line number, such as 100 television lines, can be made at the same video frequency. *(RCA Corp. and SMPTE.)*

astigmatism in the beam. If the amplitude of the signals from these two patterns is not equal, the beam has some astigmatism (ellipticity) that will favor the resolution of information in one direction and reduce it in others. The beam focus should be adjusted to produce as nearly equal signals as possible from the two parts of this chevron, to maximize the response to the two orthogonal blocks of lines.

Each block of lines is bounded left and right by a black and white block having the same transmission characteristics as the black and white line of the line patterns. These blocks produce 0 and 100 percent reference signals that eliminate tube signal uniformity and test-pattern illumination nonuniformity from the measurements. Chevrons of 400 television lines are located also at strategic positions around the pattern to allow measurement of any astigmatism.

The test pattern is designed for use with a line-selector oscilloscope equipped with provisions for displaying on the picture monitor the location of the line being examined. The desired peak signal level and proper beam setting must be established first. With the selected line positioned so that it passes through the center chevron of the test pattern, the optical and electrical beam-focus adjustments are set for maximum, and preferably equal, signals from the two chevrons. The selected line is then moved so that it passes through the appropriate television line-number block. The amplitude of this signal is measured as a percentage of the peak black-to-white signal of the adjacent blocks.

A more sophisticated way of measuring resolution takes into account the fact that the effective beam is not always symmetrical, and thus produces different resolutions along different axes of the picture. The RCA P300 test chart produces data defining the actual beam shape, thus permitting computation of the equivalent resolving characteristics of the beam. Figure 11-58 shows the central portion of this test pattern. Data to reconstruct the effective beam shape are shown in Fig. 11-59.

System and Component Resolution. The resolution of the camera tube and its coil system can be divorced from the lens used to generate the data and the characteristics of the test pattern if the MTF of the lens and the CTF of the test pattern are known. Actual tube coil system-resolution data can be determined in the following way:

1. Measure CTF of the camera tube in the system.
2. Divide the data obtained in step 1 by measured CTF of the test pattern.

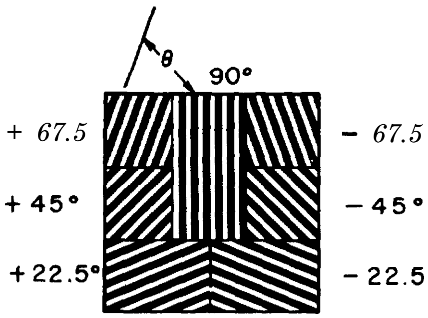

FIG. 11-58 Portion of P300 test pattern, 400 television lines slanted at various angles. *(RCA Corp. and SMPTE.)*

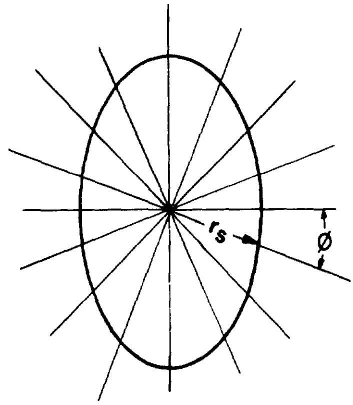

FIG. 1 l-59 Resolving aperture geometry determined from slanted test patterns (P300). *(RCA Corp. and SMPTE.)*

3. Convert the results of step 2 to MTF.
4. Divide the results of step 3 by the comparable lens MTF data.
5. Convert the results of step 4 to CTF. This will be the tube CTF

$$\mathrm{CTF} = \frac{4}{\pi}\left(\mathrm{MTF}_n - \frac{\mathrm{MTF}_{3n}}{3} + \frac{\mathrm{MTF}_{5n}}{5} - \frac{\mathrm{MTF}_{7n}}{7} + \cdots\right) \tag{11-10}$$

(Some tube manufacturers publish resolution data for the tube/coil combinations in this manner.)

Factors Affecting Tube Resolution. In photoconductive camera tubes, resolution is determined primarily by the photoconductor, the scanning beam size and shape, the tube size, and the number of scan lines specified by the system standards.

If the photoconductor is nondispersive of light and has good optical absorption, and little lateral leakage caused by a conductive layer of the scanned surface, the photoconductor will not limit the resolution for even very small size tubes. The scan-line pitch of a 525-line system on the popular 18-mm-diameter (0.66-in) tube is 13.2 μm. The thickness of photoconductors ranges from 1.5 μm for antimony trisulfide through 4 to 5 μm for Saticon photoconductors to 12 to 13 μm for lead oxide tubes. Even if light is dispersed by the antimony trisulfide photoconductor, it cannot scatter any appreciable distance because of the thinness of the material. At the other end of the range, lead oxide is about as thick as the scan line pitch, allowing greater dispersion and resolution loss. In silicon diode tubes the resolution is ultimately limited by the number of diodes in the diode array.

The electron beam has the major influence on camera tube resolution. Very small size beams can be produced, but they may be limited in current capabilities. Operation of the tube elements, particularly the mesh electrode and electrodes that control the beam velocity at high voltage, will produce higher-resolution beams. The use of excess beam in the setup of the tube can also degrade resolution.

The scanning-line standards determine the upper resolution of a system in the vertical direction. System standards initially recognized the fact that the vertical resolution is limited to 70 percent of the number of scan lines (commonly called the *Kell* factor). Resolution is highest in a diagonal direction in a bandwidth-limited system.

The beam of a camera tube can be too small for the television system in which it is used. If the effective beam size is smaller than the scan line pitch, areas between lines will not be fully scanned. Low-frequency flicker in some areas of the pictures can result, and moving objects may be followed by a succession of light and dark images, making it appear that the scene is being illuminated by stroboscopic lights. This effect is often called *sternwave.*

The deflecting and focusing coil systems used with the camera tube also have an important influence on resolution. The design or type of these coils is usually specified when camera tube resolution data are presented, since the quality and the design of these components have a major influence on the beam size and shape.

Adjustment procedures, such as alignment and beam focusing, cannot be ignored if best resolution performance is expected.

11.6.3 LAG. Lag in a television camera tube is a measure of the rate of decay of the video signal when the illumination is changed abruptly or cut off. It is influenced by carrier-trapping effects called photoconductive lag, target storage capacitance, scanning-beam impedance, the signal level being utilized, bias-lighting level, and the amount of beam current.

Lag Terminology and Measurements. The photoconductor is a capacitor that stores the charge carriers generated by light at each point on the image and integrates these charges during the interval between successive scans of each point of the image. Immediately after the light is applied, no charge is developed, and the full signal level at each point will be built up only at the end of 1/30 or 1/25 s, which represents the frame repetition rate. When light is removed, the signal output does not drop immediately to zero, because a charge is stored on each *element* of the charge image in proportion to the integrated illumination of each point since it was last scanned. In a perfect camera tube the signal should drop off linearly during the time interval of one complete frame (two fields in an interlaced system) after the light is removed.

It has been a convention to measure the signal level during the first field after a complete frame (two interlaced fields) is scanned following removal of light. The complete lag curve commencing after the first frame interval is a better measure of lag when comparing camera tubes. This curve detects long-term persistence caused by photoconductor trapping effects and high scanning-beam impedance, and portrays the long-tail lag effects that are particularly noticeable to the eye.

Photoconductor Trapping Effects. Trapping effects in a photoconductor can produce long-lasting image retention or lag (Fig. 11-60). In the tubes illustrated, lag is dependent upon the color of light. Lag is higher for blue light in the undoped lead oxide and lower for green and red light. Lag of the doped extended-red tubes (shown here) is higher than for the undoped lead oxide types when red illumination is used. Lead-oxide photoconductors have lower storage capacitance than the same-size selenium photoconductor, but the lead oxide has more trapping effects, which can produce the characteristic *long-tail* red or blue characteristic of the pictures produced by cameras equipped with these tubes.

When a photoconductor has lag that is controlled by photoelectron-trapping effects, the lag is a variable quantity. If the exposure to light is short, the lag will be low and determined primarily by the photoconductor capacitance-beam time-constant (RC) characteristics. If the exposure is longer, the lag will be higher and caused by trapping effects. Figure 11-61 illustrates the typical lag characteristics of a photoconductor which has negligible trapping effects. The tests that produced the curves were made using different periods of exposure before the light was removed. The exposure time ranged between 2 and 256 fields (4.27 s).

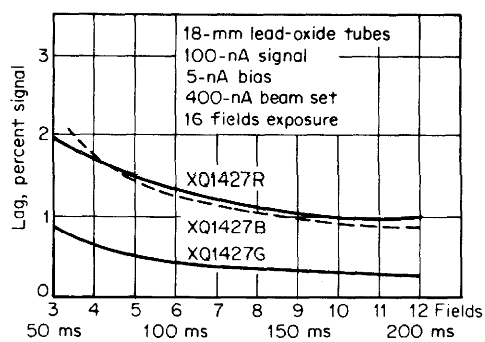

FIG. 11-60 Lag characteristics of 18-mm-diameter (0.7-in) lead oxide photoconductor tubes. *(RCA Corp. and SMPTE.)*

Figure 11-62 illustrates the lag characteristics of typical lead oxide photocon-

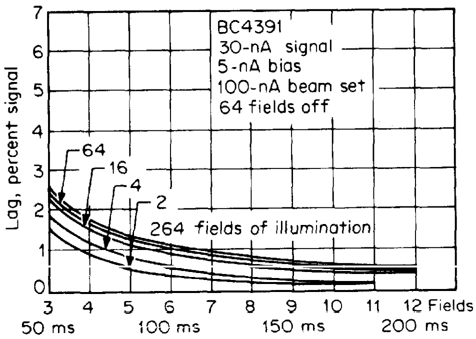

FIG. 11-61 A family of decay lag curves produced by a typical Saticon tube as a function of the exposure time before the light is removed. Low trapping (photoconductor lag) produces very little change in lag as a function of exposure time. This is also independent of the color of light. *(RCA Corp. and SMPTE.)*

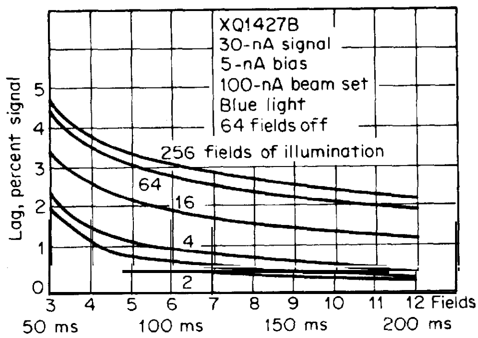

FIG. 11-62 Decay lag characteristics of a blue 18-mm (0.7-in) lead oxide photoconductor as a function of exposure time (using blue light). *(RCA Corp. and SMPTE.)*

ductor tubes. In these tubes the lag is partially controlled by trapping and/or doping effects. The measured and the subjective lags are much higher where an area is exposed for an interval longer than two fields.

11.6.4 LAG-REDUCTION TECHNIQUES. Lag can be progressively reduced by employing several methods. The effects are cumulative, as illustrated by Fig. 11-63. This curve shows the improvements in lag of a 25-mm-diameter Saticon photoconductor tube.

Beam Impedance and Photoconductor Capacitance. When the lag of a photoconductor is not limited by photoconductor-trapping (or transit-time) effects, it is controlled by the storage capacitance of the photoconductor and the effective resistance of the scanning beam at low signal levels. The signal decays with an RC time constant determined by these factors. The photoconductor storage capacitance is the capacitance formed by the two sides of the photolayer, with the photoconductor itself being the dielectric (Fig. 11-64).

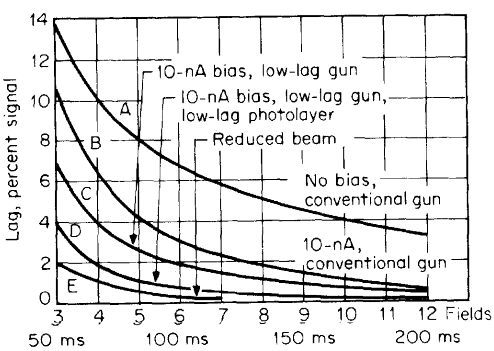

FIG. 11-63 Progressive improvement in lag of 25-mm-diameter (1-in) Saticon tubes operating with 50-nA signal current by utilizing bias light, a low-impedance (low-lag) gun, a low storage capacitance photoconductor, and beam reduction made possible by automatic highlight overload compensation circuitry (bias: 10 nA). *(RCA Corp. and SMPTE.)*

The scanning-beam resistance results from beam electrons having a range of velocities in the direction perpendicular to the photoconductor. The scanning-beam electrons approach the photoconductor with nearly zero velocity perpendicular to the surface. When the beam drives the surface to zero, or cathode voltage, the excess beam electrons return again toward the gun. Those electrons in the scanning beam with the highest velocity will land on the photoconductor last and drive the surface slightly more negative than will others with lower velocity. On successive scans of that point, if it remains unilluminated, the higher-velocity electrons will drive the scanned area even more negative and produce a small amount of signal current each time until an equilibrium voltage is reached. This situation produces a residual or lag signal.

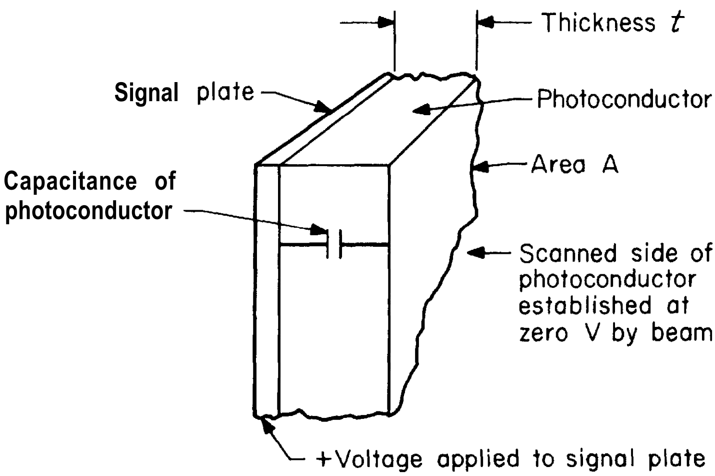

FIG. 11-64 The photoconductor as a storage capacitor. *(RCA Corp. and SMPTE.)*

A resistance value can be assigned to the electron beam. A plot of collector voltage versus current collected from the beam is shown in Fig. 11-65. At a negative collector voltage, no current will be collected. At a high collector voltage, all electrons will be collected, as in the case of a high positive charge image on the photoconductor. The transition curve between these conditions represents beam resistance: $R = (\Delta I/\Delta E)^{-1}$.

R in series with the photoconductor C produces the effective RC time constant that determines the shape of the decay curve. Reducing either C, R, or both will decrease the lag.

Reduction in Capacitance. The viable options available to decrease the capacitance are: (1) Decrease the scanned area, and (2) increase the thickness or decrease the dielectric constant of the photoconductor. Decreasing the scanned area allows the production of a smaller tube. Increasing the thickness of the photolayer decreases the capacitance. Antimony trisulfide and lead oxide photoconductors are made porous to some extent to reduce the effective dielectric constant.

Beam Resistance. The beam resistance can be altered by the design of the electron gun. Rossmalen pointed out that the mutual repulsions of electrons in the high-density region occurring in the beam crossover portion of the beam path in a conventional electron gun (Fig. 1 l-66) can cause a spread in the velocities of the electrons. B. H. Vine showed that a diode-type gun could limit the axial spread of electron velocities and contribute to a lower beam impedance. Careful design of a conventional triode electron gun can minimize the charge density in the crossover and reduce lag, as illustrated in Fig. 11-63, curves B and C.

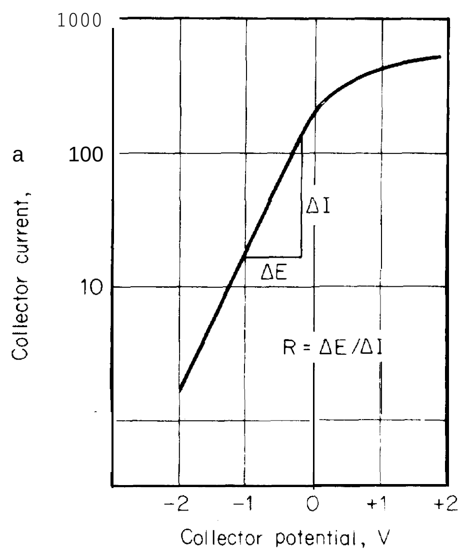

FIG. 1 l-65 The beam acceptance curve of a low-velocity electron beam used to establish the effective resistance of the beam. *(RCA Corp. and SMPTE.)*

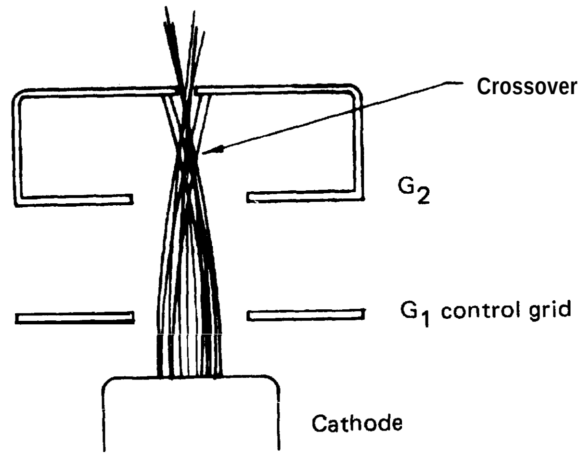

FIG. 11-66 **Cross section of a conventional triode gun showing the high electron density crossover region that can contribute to high beam resistance.** *(RCA Corp. and SMPTE.)*

Operating Conditions and Beam Impedance. The beam impedance is a function of the beam current. When excess beam current is used, the effective beam resistance is increased, and lag increases. Figure 11-67 shows the progressive decrease in lag as the beam current is decreased. This improvement is possible in cameras designed to use highlight-sensing circuits that provide extra beam current to instantaneously handle brighter-than-normal scene highlights when they occur.

Bias Lighting. Bias lighting is perhaps the most effective method of reducing lag. With bias lighting, a small amount of uniform illumination is applied on the photoconductor. The amount of bias light usually is enough to develop a uniform signal current from 5 to 10 nA.

The charge voltage developed by the bias light raises the voltage on the scanned side of the photoconductor in the absence of scene light to a level that is near the effective velocity spread of electrons within the beam.

The beam lands more fully on the lowest charges developed by light from the scene image. Under these conditions the beam has a low resistance, and the lag is substantially

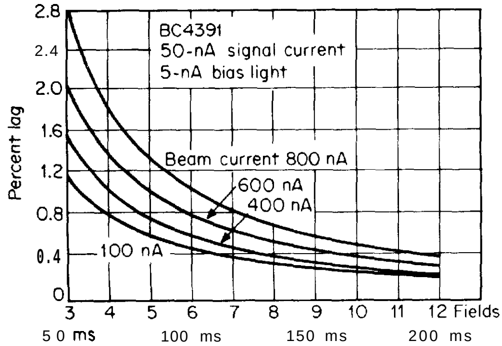

FIG. 11-67 **The progressive reduction in lag by reducing the amount of beam current.** *(RCA Corp. and SMPTE.)*

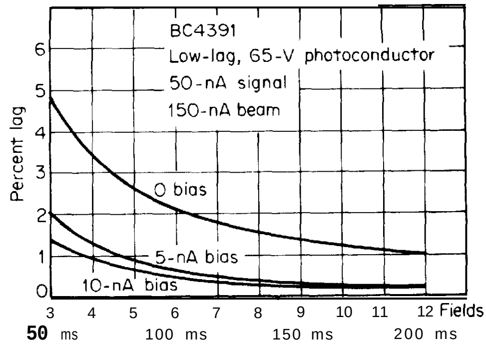

FIG. 11-68 **Progressive improvement in lag from an 18-mm (0.66-in) Saticon tube as a function of bias light level.** *(RCA Corp. and SMPTE.)*

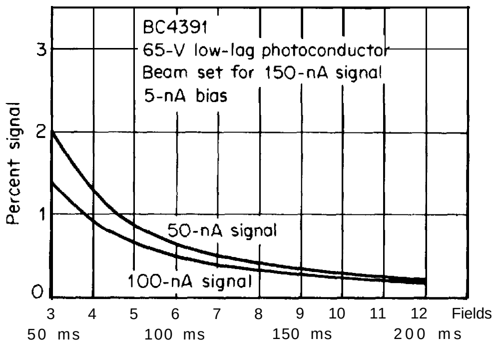

FIG. 11-69 Lag as a function of signal current in an 18-mm camera tube. *(RCA Corp. and SMPTE.)*

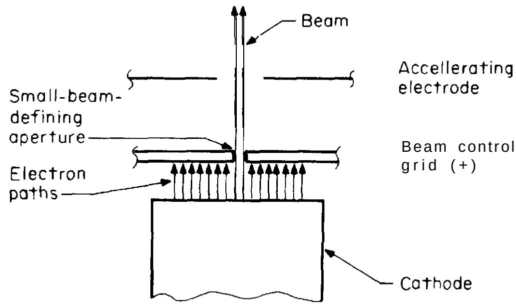

FIG. 1 l-70 Diode-gun configuration.

reduced. Bias light does not reduce the contrast, since the added dc signal level is canceled in the signal-processing amplifier. Figure 11-68 shows the progressive improvements in lag as bias lighting is increased. Lag is also a function of the signal current, as illustrated by Fig. 1 l-69. This fact must be taken into consideration when applying bias light to a camera in which the signal current for white light is different in the different channels.

Lag is never reduced to zero. In a color camera the amount of bias light in the three channels should be roughly in inverse proportion to the operating signal current level in each channel for best lag performance.

Diode Gun Tubes. Diode gun tubes are camera tubes with a gun structure designed so that the G_1 control grid is run positive with respect to the thermionic cathode. This prevents a space charge from altering the velocity spread of the electrons. The configurtation is different for different designs, but all have in common an electron beam that flows nominally parallel to the axis without developing a high current-density crossover region. The intent is to minimize beam impedance and produce a beam with as narrow a divergence angle as possible, to maintain good resolution of the focused beam.

A diode gun allows design-change flexibility. In lead oxide tubes the reduced beam impedance permits a thinner, and hence higher-capacitance, photolayer without increasing lag. This thinner photoconductor layer has higher resolution than a thick layer. When used with a photoconductor such as a Saticon layer, whose resolution does not depend on thickness, slightly higher resolution is produced by the small beam divergence angle from the diode gun.

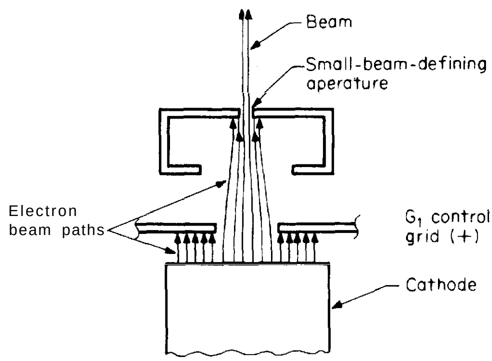

FIG. 11-71 Diode and triode beam resistance or equivalent temperature determined from collector voltage-current curves.

A diode gun has the structure and beam electron trajectory as shown in Fig. 11-70. The beam resistance and the equivalent beam temperature of conventional triode and diode guns are shown in Fig. 11-71.

In some designs of this type of gun, *diode gun* may be a misnomer. In actuality, it is a triode gun operated in a positive G_1 mode. The scanning beam in this gun is formed at a small aperture in a third electrode (Fig. 11-72).

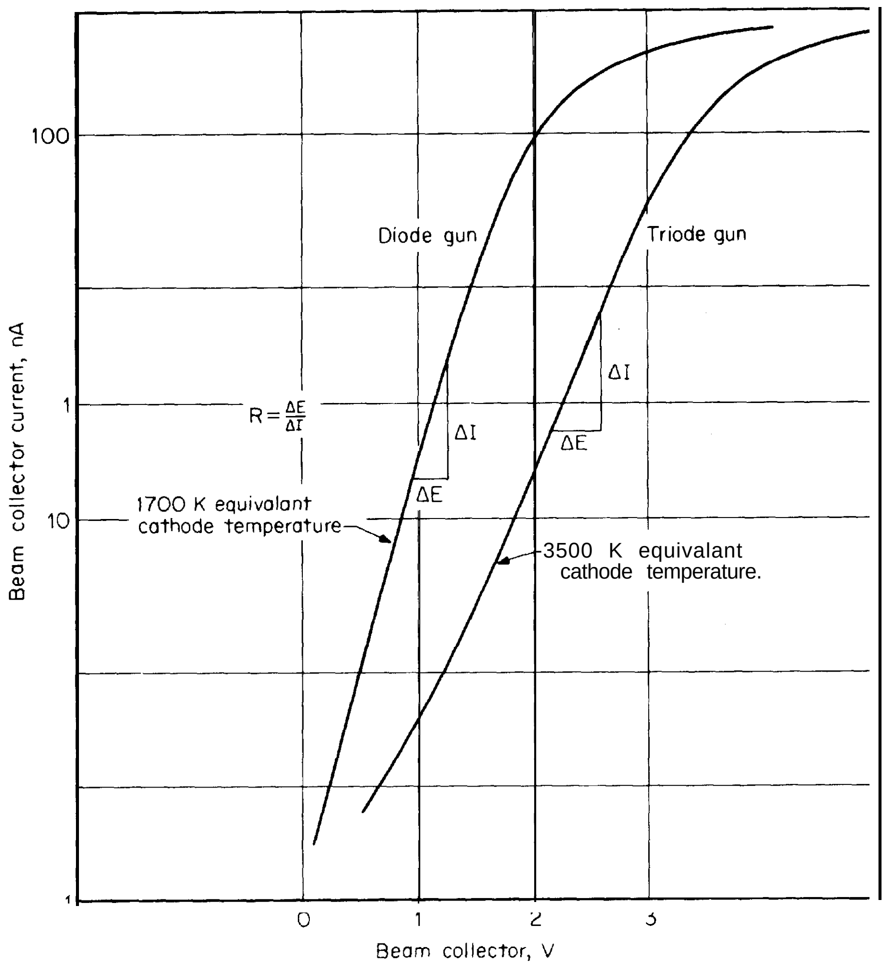

FIG. 11-72 Positive-grid triode, sometimes called a diode gun.

11.7 SINGLE-TUBE COLOR CAMERA SYSTEMS

Most low-cost home use cameras, and many professional color cameras, utilize a single camera tube to produce the complete color television signal. Nearly all these tubes incorporate an array of fine color stripes from which the color information is derived. These tubes are vidicon types; i.e., they use a photoconductor to detect the light and use a target readout.

There are two categories of these tubes. One has a single output, and the color signals are derived by retrieving color information from high-frequency carrier signals present in the output signals. The other utilizes multiple output signals from multiple discrete-signal plate structures inside the tube. Most conventional camera tubes having adequate resolution and color response can be utilized in a single-tube color camera by imaging the scene onto an appropriate color striped-filter array and reimaging this image to the faceplate of the tube. The tube then acts as a single-output, single-color tube.

Some camera designs have also been made in which a single tube produces all the color information and a second tube produces the luminance and detail information of the composite color signal.

11.7.1 SINGLE-OUTPUT-SIGNAL TUBES. A typical stripe color system will use two different sets of stripes from which three-color information can be derived. One example is the structure shown in Fig. 11-73. Yellow (Y) stripes are utilized to produce blue information, and cyan stripes (C) are used to detect red color information. The sets of stripes are inclined from one another so that there are two different color carrier frequencies developed as the beam scans across these periodic structures. When blue light is present in the scene, no blue light will pass through the yellow filter lines, but it will pass through the open areas between the yellow lines, including that portion covered by the cyan filter. This will produce a blue carrier signal in the output. Similarly, red light will be absorbed by the cyan filter and will be transmitted through the space between the cyan filters (including the portion of the yellow filter in this space), producing a red carrier signal in the output. The frequency domain of the output signal is shown on Fig. 11-74. The information below the color carrier frequencies is extracted to form the white or luminance signal (Y), and the two-color carriers are detected separately as shown in Fig. 11-75. The amplitude-modulated color carriers are then detected to produce separate red and blue signals. Subtracting (matrixing) these two signals from the luminance signal will produce a green signal, as illustrated in Fig. 11-76.

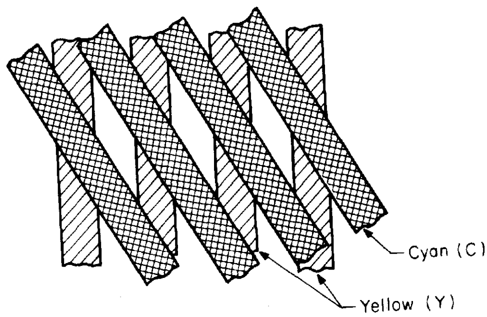

FIG. 11-73 Dual sets of color stripe filters.

The beam size of the camera tube does not have to be small enough to resolve each line with 100 percent contrast to produce a color picture. Low resolution of either the beam or the photoconductor will result in low color-signal levels and poor color-noise performance, but will not necessarily result in poor colorimetry. Loss of resolution during operation will produce a fail-to-green mode since luminance information will remain constant while red and blue information will drop.

A variation of the stripe-filter design can produce a single-carrier system that contains red and blue information which can be extracted later. The filters are configured as shown in Fig. 11-77. They are angled so that at each successive scanning line, the carriers produced by the lines slanted clockwise advance in phase by 90° and the ones slanted counterclockwise drop back by 90” (Fig. 11-77, lines A and *D*). If the line 1 information is stored in a 1*H* delay and line 3 is delayed for 90” of the carrier frequency, the red information on line 3 compared with line 1 (delayed) will be exactly 180” out of phase (*A* and E). The blue information on line 1 (delayed 1*H*) compared with line 3 (C and *F*)

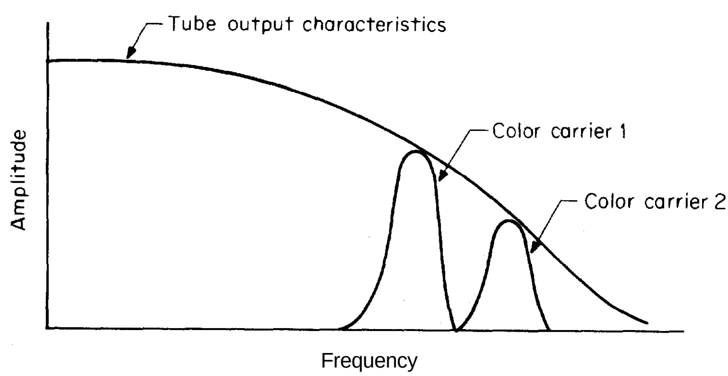

FIG. 11-74 Frequency **characteristics of a two-carrier single-tube** color camera **tube.**

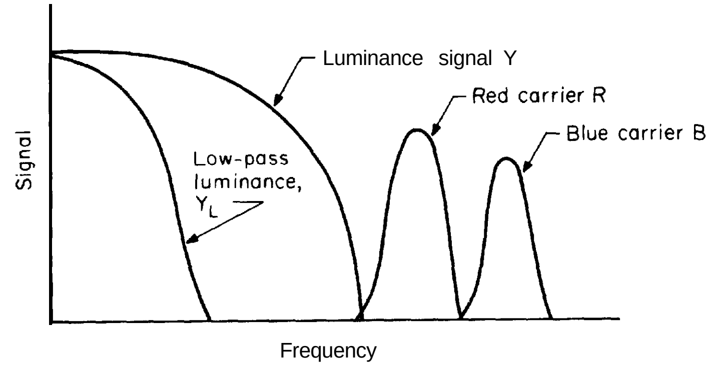

FIG. 11-75 Signals extracted from the color tube output.

will be *in* phase. If the two signals are added, red information will cancel and blue signals will add, producing a blue signal carrier. If the two signals are subtracted, the blue signals will cancel and the red signals will add to produce a blue carrier. These two carriers can then be detected to produce the blue and red signals (Fig. 11-78).

Other systems proposed, but not widely used, employ parallel vertical stripe filters that consist of triplets of different colors. These systems operate on a system of synchronous detection. This means they can recognize the position of the beam relative to the stripes so that the detector can sequentially interrogate the signal being developed by the beam over a particular stripe anddivert that signal into an appropriate color channel. Recognition of the position of the beam is determined from an additional black or white reference stripe that can be detected (to time the synchronous detector). These systems suffer from color fidelity if the beam is not as narrow as the color stripe. Timing of the synchronous detector is uncertain if the reference signal becomes ambiguous in the presence of other video information.

Basic Design of Single-Color Tube. High-resolution photoconductors such as antimony trisulfide, **Saticon,** Newvicon, or Chalnicon are used because of their inherent resolution and color response. The electron optical systems utilized are of superior quality for resolution and resolution uniformity, since color level and color uniformity depend upon high resolution and resolution uniformity, respectively. The filters are incorporated in the tube between the faceplate and the signal plate (or plates), and a barrier layer produces a smooth substrate for the signal plate and the photoconductor plate (Fig. 11-79).

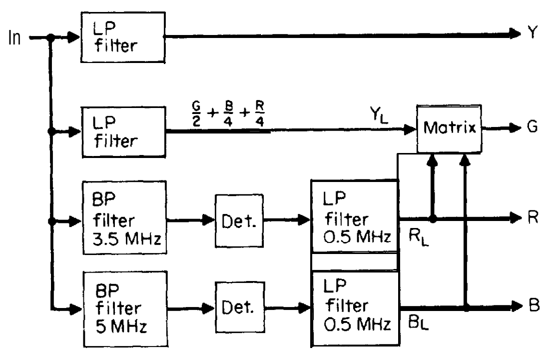

FIG. 11-76 System block diagram of a two-carrier system. *(RCA Corp.)*

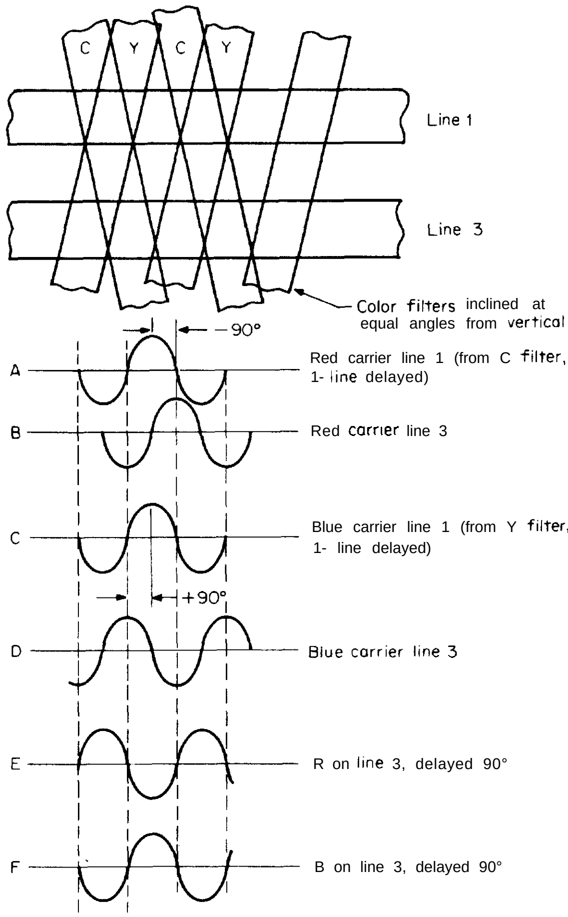

FIG. 11-77 Configuration and phase relationship of the interleaved color carriers in the single-carrier system.

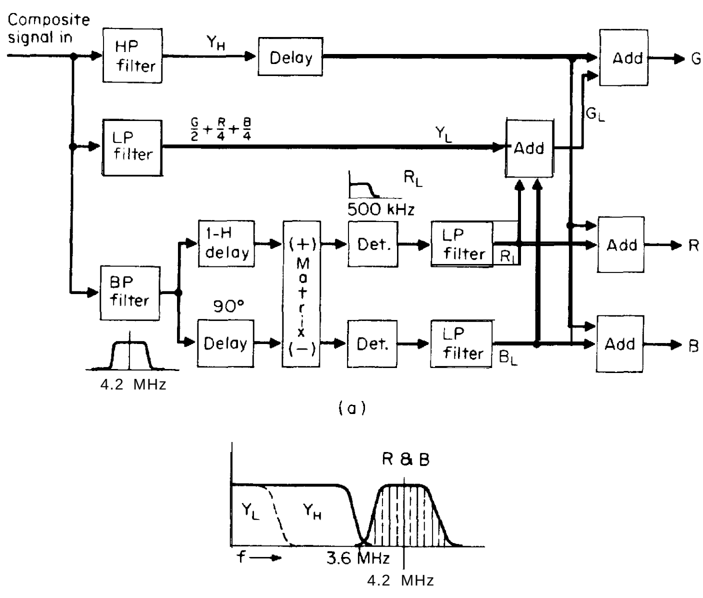

FIG. 11-78 Single-carrier system: (a) decoder employing 1-H delay comb filter and (*b*) typical frequency spectrum. *(RCA Corp.)*

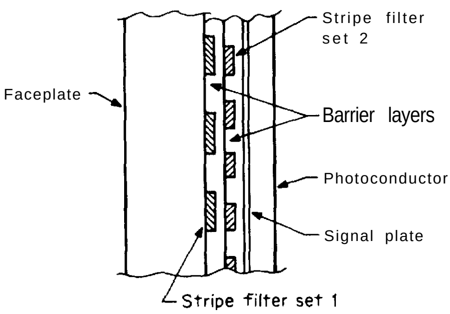

FIG. 11-79 Cross section of typical multistripe color tube target construction.

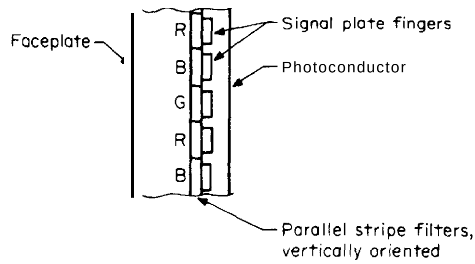

FIG. 11-80 Cross section of trielectrode color vidicon.

11.7.2 MULTIPLE-OUTPUT-SIGNAL TUBES. Two single-tube color vidicons have been developed using multiple-output signals. The trielectrode vidicon has three outputs from three independent sets of signal plates, each associated with a set of appropriate color filters. The *Trinicon* has two separate output terminals from the target.

The trielectrode vidicon has a filter structure consisting of vertically oriented triplets of red, blue, and green filters. Each filter stripe is backed up by a transparent signal plate. All the red, blue, and green signal plate stripes are tied together to their respective output pins protruding through the faceplate (Figs. 11-80 and 11-81). Even if the beam is larger than the stripes, the signal produced at each signal stripe will relate only to the color of light coming into the photoconductor through its associate color filter. This preserves color fidelity and prevents loss of color information in noise at low light levels. High-frequency detail information is cross coupled into all channels because of the high interelectrode capacitance.

The Trinicon tube has vertically oriented color stripes and is designed and operated to produce an unambiguous phase-reference signal that can be used to synchronously detect the color signals from the output signal.

The Trinicon tube has two separate outputs that are connected to two sets of interleaved signal plate fingers. Vertical triplets of red, blue, and green filter stripes are positioned in front of these fingers as shown on Fig. 11-82. There are three filter stripes for

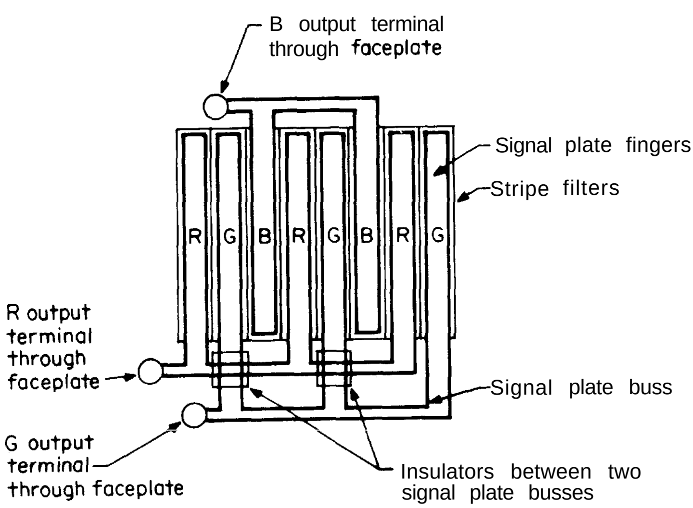

FIG. 11-81 Trielectrode vidicon structure schematic.

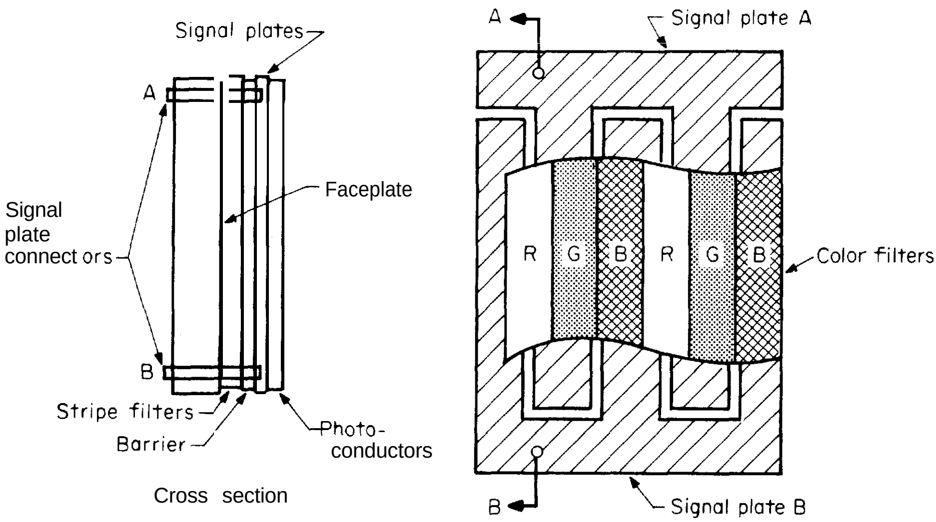

FIG. 11-82 Cross section and plan view of Trinicon showing relationship of stripe filters to the signal plate fingers.

each pair of interleaved fingers. The filters are located so that one color filter stripe straddles the gap between two fingers and the other gap coincides with the junction between the other two color filter stripes. During operation, the voltage between the two fingers is changed on every other scan line so that alternately one set of fingers and then the other is more positive.

The signal output from the photoconductor which is behind the signal plate fingers and filters that are more positive will be higher than the signal produced behind the low-voltage fingers. This is illustrated in Fig. 11-83. It is shown that in line 1, among other differences, the red signal is different on one side of the filter than on the other. This situation is reversed on line $n + 1$ since the voltages on the signal-plate fingers are reversed.

The signals are processed as shown in Fig. 11-84. The outputs from both signal plates are coupled into the same amplifier through a small transformer. The signal is delayed for exactly one horizontal scan-line interval. The active and the delayed scan line are then added, as well as subtracted (Fig. 11-84). The sum of the two produces the proper video output corresponding to the light and color filter transmission. When the signals are subtracted, the video signals cancel and a properly phased index signal is generated that is then used in the synchronous detector to key the sequential color signals into the proper color channel.

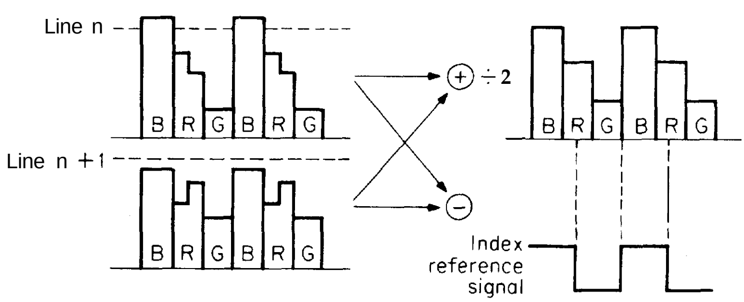

FIG. 11-83 Alternate-line signal output from Trinicon tube.

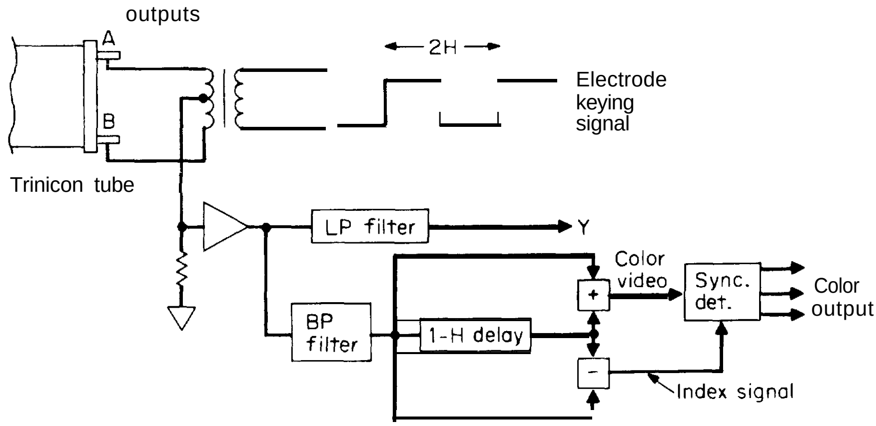

FIG. 1 1-84 Trinicon tube and signal-processing block diagram.

11.8 SOLID-STATE IMAGER DEVELOPMENT

The technological developments for fabricating and manufacturing solid-state imaging arrays with the objective of achieving performance which is competitive with that of camera tubes was started 20 years ago. The earliest devices to employ self-scanning were arrays of thin-film transistors (TFTs).[4] Since then the extensive activity directed toward the perfection of large-scale integrated circuits using silicon technology has provided a rapidly expanding base of manufacturing technology and facilities which can be applied to imagers. In the United States, the complexity and high production cost of solid-state sensor arrays initially limited their use to applications employing single-line scanners and small-area arrays. The limited number of large-scale arrays produced by Fairchild, RCA, and Texas Instruments were most widely used in scientific applications where radiometric and geometric accuracy in a video output was of particular importance.

With the rapidly expanding markets for closed-circuit television systems and home video recorders, several Japanese manufacturers have made an intensive effort to develop a single-sensor solid-state color camera, comparable in performance with counterparts using camera tubes.

11.8.1 EARLY IMAGER DEVICES. The first solid-state imagers consisted of two-dimensional arrays of photosensing diodes. The operating potentials were provided by x and y bus bars, and the signal from an individual sensor was sampled by activating on-chip switching circuits as shown schematically in Fig. 11-85. An imager of this type having a checkerboard of color filters is used in a VCR color camera introduced by Hitachi in 1981.[5]

Various design concepts were developed for an on-chip output stage to detect the signal from successive pixels as required for a video output. At this time, the most successful means for eliminating the characteristic fixed-pattern noise of the x-y addressed devices is that included in the Hitachi camera.

A more complex type of x-y addressed imager called a *charge injection device* (CID) is being marketed by the General Electric Co.[6] The sensing element of this architecture consists of an isolated pair of MOS capacitors. As the integrated photocharge is shifted from one capacitor to the other, its amplitude can be sensed by one of the bus bar lines. This nondestructive readout provides a unique capability for multiple readout of one frame of data. Erasure is achieved by dumping the charge into the substrate.

11.8.2 IMPROVEMENTS IN SIGNAL-TO-NOISE RATIO. The introduction of internal charge transfer concepts such as the bucket brigade[7] and the charge-coupled device’ (CCD) opened the way to the development of area sensors with improved signal-

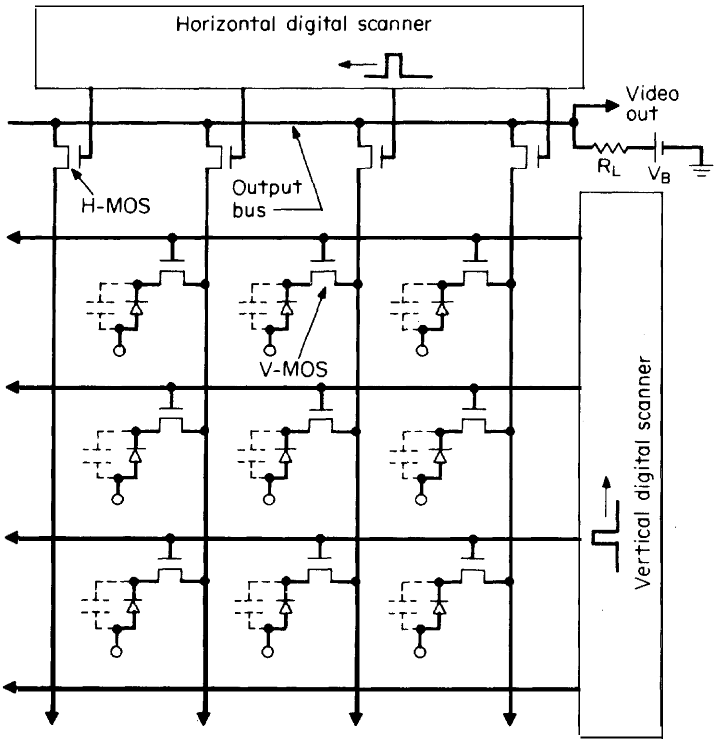

FIG. 11-85 A schematic diagram of an x-y addressed imager with an MOS switching transistor at each pixel.

to-noise performance at low light levels. This results -from the capability to move the packets of photocharge from the sensor site to the output stage by controlled transfer through the silicon substrate. The effective output capacitance can be less than 1 pF, providing an rms noise per pixel of 50 electrons or less from an imager having a full pixel charge of 2 X 10^5 electrons. This was accomplished with an off-chip signal processor employing correlated double sampling that eliminates the reset noise of the charge-sensing floating diffusion and the $1/f$ noise of the output transistors.

11.8.3 CCD STRUCTURES

Frame-Transfer Structure. There are two basic structures for CCD imagers. The *frame-transfer* structure shown in Fig. 11-86a is one. The photocharge is generated by the illumination incident on the image register. At the end of the exposure interval (1/60 s for United States standards) this entire charge pattern is transferred in parallel through vertical CCD columns into the storage register, thereby freeing the image register to begin the integration of the next field. During this same time interval the charge packets in the storage register are transferred one row at a time into the output register through which they are transferred serially to the output stage. When all rows of the storage register have been read out, this register is ready to accept the next parallel transfer from the image register, and the entire operating cycle repeats.

Interline-Transfer Structure. Shown in Fig. 11-86b is an interline-transfer structure, the second basic structure for CCD imagers, in which columns of photosensor elements alternate with CCD transfer registers. During the optical exposure, charge is generated in the photosites. At the completion of the exposure/integration period all packets are shifted into the neighboring stage of the adjacent CCD column. These charge transfer

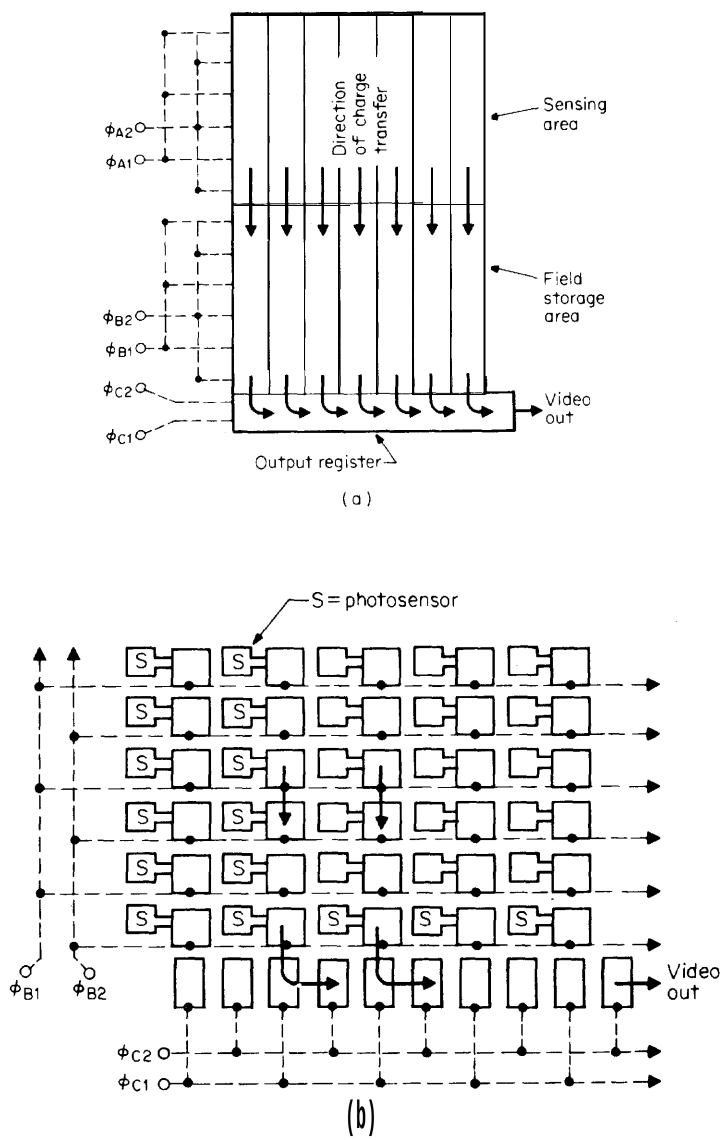

FIG. 11-86 CCD imager architectures: (a) frame transfer structure; (b) interline transfer structure.

columns are the equivalent of the storage register of the frame transfer structure. After all rows of signal charge have been shifted into the output register and transferred to the output stage, the operating sequence is repeated.

During the early stage of CCD-imager development, when the transferred charges were moved along the surface of the silicon substrate adjacent to the gate structure, there was a significant amount of charge left behind as the result of surface state trapping. The smaller number of transfers, required by the interline-transfer structure was an attractive feature. The subsequent development of buried channel structures in which the movement of charge takes place in an n-doped channel formed on a p-doped substrate **eliminates surface trapping losses and provides a significant increase** in charge transfer efficiency.

Because the charge-transfer columns of the interline-transfer structure must be cov-

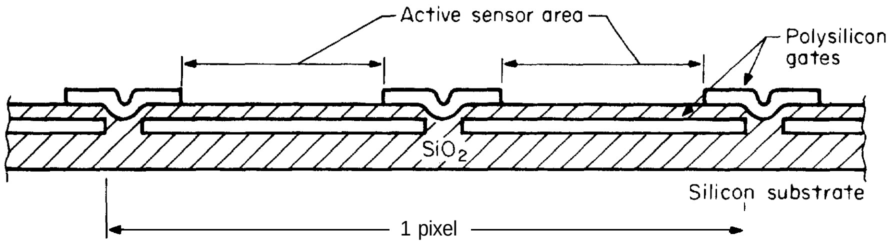

FIG. 11-87 A cross section of a typical multilevel polysilicon gate structure used in CCDs.

ered by an opaque mask, only a part of the area illuminated by the light is photosensitive. This reduces the area utilization of the incident photon flux to the order of 30 to 50 percent. Similarly, frame transfer imager structures which are illuminated on the structured side waste incident radiation through absorption in the multilevel gate structure such as that diagrammed in Fig. 11-87. Only those photons which are absorbed in the substrate are capable of generating photocharge. A variety of gate structures with transparent windows have been devised to increase device sensitivity.

11.8.4 NEW DEVELOPMENTS. The introduction by RCA of rear-illuminated thin substrate devices has made available frame-transfer imagers with full-area utilization of the incident light. By assuring that the depletion region extends across the full thickness of the 10-μm-thick substrate, quantum efficiency comparable with the silicon-target vidicon is obtained. Figure 11-88 shows the reported quantum efficiency as a function of wavelength for several different CCD imagers.

The latest generation of solid-state imagers has 10- to 20-μm wide pixels which are 15 to 30 μm long. Horizontally there are between 300 and 500 elements and, with interlace, 500 elements vertically. Because the modulation transfer function remains high out to the Nyquist limit, this number of pixels gives acceptable dynamic image detail for most applications. The illumination-to-signal transfer function is close to linear over the full dynamic range which typically exceeds 10^3. Not unexpectedly, these new and complex structures have certain undesirable characteristics not encountered in camera tubes. While these new devices are free of image lag, even at low light levels, they are subject to image blooming when exposed to a light overload. This has been overcome by adding complexity to the pixel structure.

There is an additional problem of transfer smear which is the result of spurious charge generated in high light regions of the scene contaminating the signal from low-light regions. Since this effect is limited to the direction of charge transfer, it tends to produce low-contrast vertical bands in the video output. Again, this defect has been reduced or eliminated by adding further complexity to either the device architecture or the camera.

By taking advantage of the continuously improving quality of silicon wafers and the better understanding of processing constraints which must be respected, there has been continuous improvement in the yield of cosmetically acceptable devices over the past 10 years. The density of both high dark current and low sensitivity pixels is directly related to the processing cycle used to fabricate the device. A high density of crystalline anomalies which are potential defect sites is present in the best quality silicon wafers. The number which become electrically active is controlled by the wafer processing both before and during device manufacture.

In this brief review of solid-state imager development all discussion of device physics has been omitted. Listed in the references are several publications dealing in detail with this aspect of an ongoing technological development.[2,6,9,10] A 1983 review of the reported performance for the large number of architectures which have been devised and fabricated either as laboratory or manufactured products is given in Ref. 11.

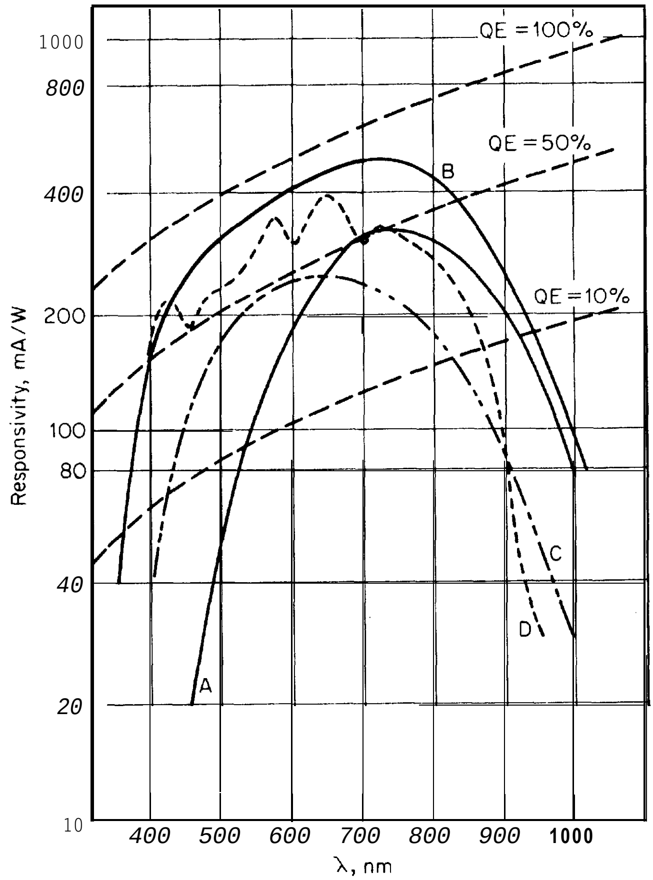

FIG. 11-88 Responsivity-vs.-wavelength curves for image sensors employing MOS-capacitor sensing elements. Curve *A*: front-illuminated CCD imager with single-level polysilicon gates. Curve B: rear-illuminated thinned, glass-laminated CCD imager. Curve C: front-illuminated virtual-phase CCD imager. Curve *D*: front-illuminated CCD imager with transparent second level gates. Dashed lines indicate, at different wavelengths, the varying relationship between responsivity and quantum conversion efficiency (QE) at levels of 10, 50, and 100%.

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