A Charge Storage Target for Electron Image Sensing

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A charge storage target consisting of a dense array of silicon photodiodes has been described as the image-sensing element in a vidicon type of camera tube for the **Picturephone®** *station set. The target stores a spatially distributed charge pattern corresponding to an optical image in the form of a partial discharge of the reverse-bias voltage of the diodes. The discharge results from leakage current associated with hole-electron pairs created in the silicon substrate by incident photons during the raster interval. Recharging of the diodes to the full reverse-bias voltage along a prescribed raster by the scanning, low energy, electron beam creates the desired video signal.*

This paper describes creation of the hole-electron pairs in the silicon substrate by impinging high energy electrons. Since these electrons, incident from the side opposite the diode array, create a multiplicity of pairs, charge gain results. As in photon sensing, the discreteness of the array allows preservation of detail in the spatial distribution of impinging electrons. Measurements of charge gain as a function of electron energy and target resolution are presented.

Applications in scan conversion, low light level TV, X-ray image intensification, and electron microscopy are indicated.

I. INTRODUCTION

The subject of this paper is the use and properties of a self-supporting silicon wafer containing an array of about one-half million diodes in an area of 12.5 millimeters on a side. See Fig. 1. The thickness of the substrate under the diode array is in the range 10-25 microns depending on the application. The wafer perimeter which is considerably thicker, provides increased physical strength. As an image sensing target in a vidicon type of camera tube,[1] developed for the *Picturephone®* station set,[2] it converts incoming photons that are absorbed in the n-type conductivity substrate into hole-electron pairs.

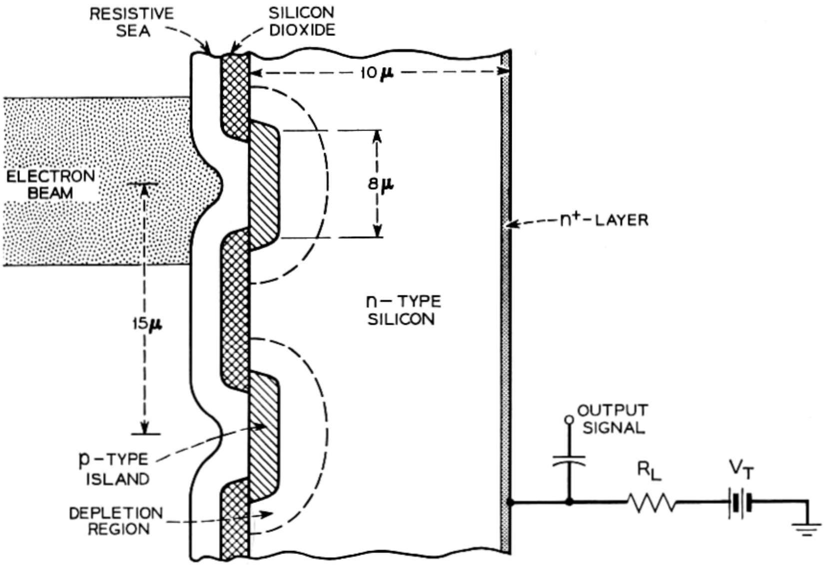

Fig. 1 — Cross section of active target area illustrating the substrate, diodes, oxide mask, resistive sea, and scanning electron beam.

Except for those holes created within a surface layer, a few thousand angstroms thick opposite the diodes, there is virtually unity probability that any minority carrier hole can diffuse to the depletion region of one of the normally reverse-biased diodes. The hole is swept across the depletion region to the diode p-type conductivity region and contributes to the total leakage current of the diode. The totality of holes reaching the diode during a raster interval, partially discharging the diode, constitute a stored charge proportional to the integrated local intensity of the photon flux. Recharging of the diode by a scanning, low energy electron beam creates a current in an external circuit which constitutes the desired video signal. The recharged diode is primed for integration of the hole flux during the next interval by the same process. Figure 2 illustrates the performance on one such target illuminated by a conventional TV test pattern and scanned in a 525-line raster with a frame interval of 1/30 second. Other forms of radiation will create hole-electron pairs in a silicon substrate. Figure 2 therefore indicates the potential performance for imaging these as well.

In this paper the radiation of interest is energetic electrons. An energetic electron, impinging on silicon will create 286 hole-electron pairs per kiloelectron volt of kinetic energy.[3] When the holes can diffuse to the nearest diodes with high probability, the resulting charge exceeds the charge incident on the target and amplification results. Thus the target, in conjunction with scanning, video processing, and display is an electron image transducer. It has the potential of being useful in any one of a large number of systems or devices in which it is desired to convert spatial intensity variations in incident radiation into a visible image. For example, image intensifiers transduce an optical image into an equivalent electron image by absorbing the incident light on a large area photocathode. The resulting low energy electron image is refocused at high energy onto a second plane by an appropriate electron-optical system. A phosphor screen transducer placed in this plane produces an intensified optical image. The electron image in an electron microscope similarly is viewed by a phosphor screen transducer. The addition of a transducer for X-rays to light

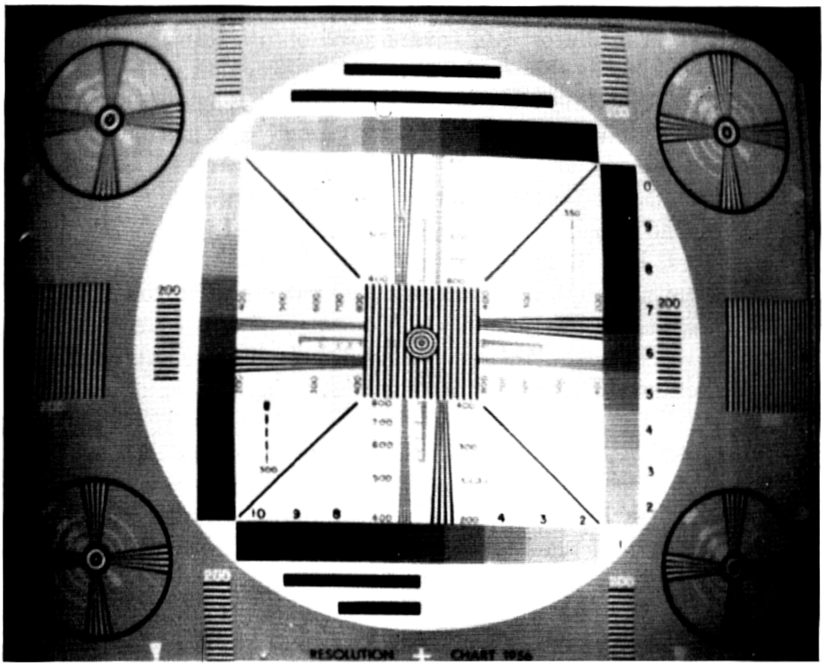

Fig. 2 — Monitor display illustrating performance of diode array target in a camera tube.

at the front end of an image intensifier allows X-ray image intensification. The transducer would be a phosphor screen photon-coupled to the photo-cathode of the image intensifier.

In all of these applications it is becoming common practice to view the output phosphor screen with a closed circuit TV system. This allows observation of a magnified, bright image with the ability to perform video processing and to produce a permanent record on video tape. In these cases, especially when a direct visual output is not really necessary, a single stage electron-to-video transducer with charge amplification replacing the output phosphor screen, lens, and pickup tube would effect a considerable simplification in the system with savings in volume and cost and would afford the possibility of better performance.

Indeed in a class of pickup tubes exemplified by the secondary election conduction (SEC) camera tube,[4] the fundamental image sensor is a photocathode, and the electron image is focused at high energy onto a charge storage target with charge gain. The target is scanned in a vidicon fashion to produce the video output. In this case the target is an insulator, KCl, evaporated onto a thin metallic back-plate. The charge in this case is created in a region of high electric field, and the resulting electrons are swept out. The remaining positive charge is immobile and constitutes the storage mechanism. Such a target is similarly an electron-to-video transducer with charge gain and has been used in the applications suggested above.

In a second class of applications exemplified by double beam storage tubes, Fig. 3, the input electrons are produced by a writing gun and form an amplified, stored charge pattern. The stored pattern could represent, for example, a video display, as in a scan conversion device,[5] an oscilloscope trace for highspeed, nonrepetitive events[6] or a closed, nonintersecting path for variable delay of analog or digital signals.[7]

The double-beam device of Fig. 3 has been chosen as the vehicle for study of the target imaging characteristics under electron bombardment. The target has also been studied under conditions which allow multiple readout of the stored charge. In what follows the double-beam device will be referred to as a scan converter.

II. THE SCAN CONVERTER

By way of introduction and for comparison, it is worthwhile to review some aspects of the target optimized for use in a camera tube.

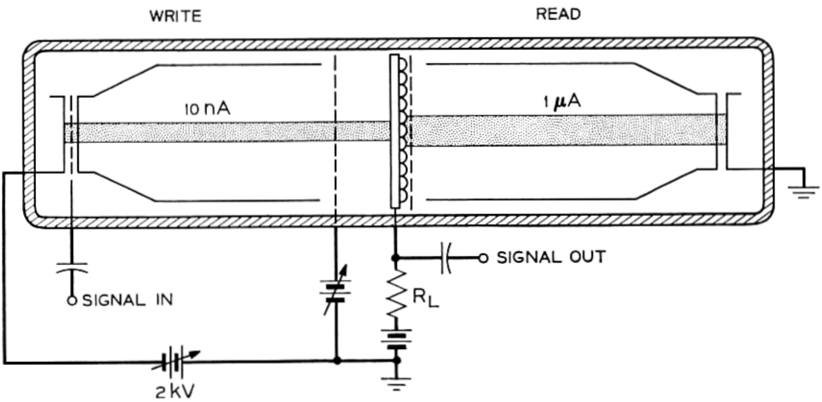

Fig. 3 — Scan converter. Notice back-to-back gun structure.

The array of reverse-biased diodes stores positive charge, created in the form of minority carrier holes by photons incident on the n-type silicon substrate from the side opposite the diode array. The holes diffuse to the diode depletion region and are swept across to the p-region or island of the diode. The stored charge is manifest as a partial discharging of the diodes from their full reverse-bias voltage, which equals the fixed potential of the target substrate, V_T, relative to the potential of the electron beam cathode. The scanning, low energy electron beam, landing on the exposed p-islands, periodically charges them toward cathode potential. Full recharging brings the potential of the p-islands down to cathode potential at which point the electrons can no longer land on the surface. This reestablishes the full reverse bias across the diodes.

Since the substrate potential is held fixed, the p-islands of partially discharged diodes exhibit a positive potential variation on the surface facing the electron beam. These islands are charged back to cathode potential on the next pass of the scanning electron beam. The recharging current constitutes the desired video signal and is proportional to the number of holes collected by the diodes at the position of the scanning beam. Since the number of holes stored by these diodes is proportional to the number of photons incident during the preceding frame period, the video current measures the integrated light intensity at the position of the diodes. The use of a discrete diode array preserves the spatial integrity of the incident light pattern to the extent that lateral diffusion of the holes is negligible and spatial frequencies with periods comparable to or smaller than the diode spacing are not important.

In the design of the camera tube target the proper choice of diode capacity is important as can be seen by the following example. Suppose that the peak video signal is set at 200 nanoamperes and the scanned area has 670,000 diodes. The scan time is approximately 1/30 second. The maximum charge restored to the diodes during scanning is 2×10^{-7} amperes $\times$ 1/30 second $= 6.7 \times 10^{-9}$ coulombs or 10^{-14} coulombs per diode. The voltage swing of a p-island should never be more than about 5 volts since the beam may be pulled, producing landing errors for greater values. Thus the minimum required diode capacity is approximately 10^{-14} coulombs/5 volts $=$ 2×10^{-15} farads.

Under the conditions specified, the scanning beam current required to recharge the diode to a major fraction of the full reverse-bias voltage (during the submicrosecond interval the beam is incident on the diode) is 1 to 2 μamperes. Beam currents below this value lead to image lag resulting from incomplete recharging of the diode and reduced video signal levels. If the diode capacity is doubled relative to the minimum value, keeping everything else fixed and neglecting the dependence of capacitance upon reverse-bias voltage, the voltage swing of the diode is halved.

The beam current required to recharge the diode to the same extent as in the previous case is increased significantly, possibly more than a factor of two, because the beam landing efficiency is a strong function of the landing energy and is significantly reduced if smaller voltage swings are used. (The beam landing efficiency is defined as the ratio of the surface charging current to the incident current. It is less than unity because of secondary emission and elastic reflection of electrons.) Large beam currents are not desirable and in general not practical; hence the diode capacity must be critically controlled.

For the diode geometry used in the camera tube the silicon resistivity to achieve the appropriate capacitance range is about 10 Ω-cm. The optimum capacity may be achieved by adjusting the potential of the target substrate which varies the full reverse-bias voltage.

A major requirement on the diode performance is the ability to sustain the reverse bias for an interval that is long compared with the scanning interval. With a diode dark current of 10^{-13} amperes, the time for the diode reverse bias to decay to less than half its original value without recharging is about one second, which is significantly greater than the usual 1/30 second recharging interval. The ability to hold the diode leakage current well below 10^{-13} amperes at room temperature over the necessary range of target voltage represents one of the major accomplishments of the target development program for the camera tube. Leakage current for the full array is usually well below 50 nanoamperes. A major requirement on the substrate is that volume and surface recombination rates of minority carrier holes be reduced to the point that a large fraction of the holes created by incident radiation can reach the diode depletion region.

The scan converter device is based on the charge storage and electron beam readout properties of the target. The ability to create hole-electron pairs in the target substrate by bombardment with energetic electrons forms the basis of the writing function. Writing is accomplished with a CRT type of electron beam, current modulated with the incoming video signal and incident on the side opposite the diode array (Fig. 3). Each incident electron creates a multiplicity of hole-electron pairs, some of which discharge the diodes, creating a pattern of stored charge just as in the camera tube. The charge stored in the diode array actually can be greater than the charge deposited by the incident writing beam, requiring however that the number of hole-electron pairs created per incident electron times the probability of collection for the hole, be greater than unity. The ratio of stored charge to incident charge will be called the charge gain.

Despite a possible difference in scanning rates, in equilibrium the current level of the video signal generated by the reading beam will be larger than the current in the writing beam by just the charge gain factor. (Application of the concept of charge conservation will indicate the validity of the statement.) On the other hand, the reading beam current is required to be greater than the video signal because the beam landing efficiency is substantially less than unity. Hence the writing beam will usually have much lower currents than the reading beam. In addition, the writing beam electrons will land with energies in the kiloelectron-volt range while the reading beam electrons will land with energies in the range 0–5 electron-volts. The result is that the writing beam may be much more finely focused than the reading beam. Since the penetration range of the writing beam electrons in the silicon substrate is normally under one micron, the resolution of the scan converter should be essential identical to that of the camera tube for very short wavelength light which is absorbed close to the surface.

Figure 3 indicates that some of the writing beam current could return to the writing beam cathode through the target resistor, creating an undesirable video signal. In actual fact, the potential of the mesh immediately preceding the target is adjusted to such a value that the effective secondary emission coefficient of the surface is almost exactly unity. This balance is achieved almost instantaneously so there is virtually no net writing beam current to the target (but rather the current is to the mesh) and virtually no crosstalk. In case the precise secondary emission balance cannot be achieved uniformly over the target, the secondary emission reduction in writing beam current to the target coupled with the charge gain for the desired video signal brings the crosstalk signal down to a tolerably low value.

The writing beam is scanned at a rate appropriate to the incoming video signal. On the other hand, the reading beam may be scanned at any rate desirable. Scanning the reading beam more rapidly than the writing beam produces a multiplicity of time-compressed frames as would be required for slow scan TV.

There is a technique for achieving multiple readouts while preserving the full gray scale. During the early stages of the development of the camera tube, it became clear that it was difficult, if not impossible, to obtain a stable video response unless the silicon dioxide (which covers the area between diodes and prevents beam electrons from landing on the substrate as well as protecting the diode junctions) was provided with a charge leakage path of some kind. Without the charge leakage path it was not possible to control the surface potential of the oxide and a great many deleterious effects resulted.

The scheme adopted to provide the leakage path has come to be known as "the resistive sea" and is simply the formation of a thin resistive film over the entire array. The sheet resistance of the film is chosen to allow surface leakage with a charging time constant of order one second which allows control without causing loss of resolution through lateral spreading. Additional constraints on the dielectric relaxation time and thickness of the film are required to allow complete charging of the diodes to avoid lag. These same parameters can be optimized to allow multiple readout.

Consider Fig. 4 which illustrates the target with a resistive sea and some lumped circuit equivalents for the various parameters of interest. The diode has a capacity C_d. A pulsed current source i_d accounts for the partial discharging of the diode when the writing

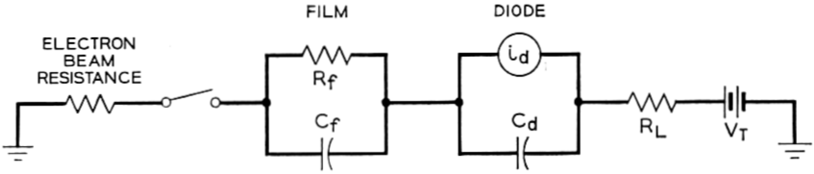

Fig. 4 — Schematic of lumped circuit equivalent for diode and resistive sea. $R_FC_F = \rho\epsilon < \tau_F = 1/30$; $C_d/C_F \ll 1$ low lag; $C_d/C_F \gg 1$ for multiple readouts.

beam is incident on the substrate adjacent to the diode. Assuming a frame compression ratio of N is desired, the video signal must be created N times for each scan of the writing beam. To maintain adequate signal-to-noise ratio the video output current must be at a level comparable with that achieved in the camera tube. This requires N times as much charge storage; hence the diode capacity must be about N times larger than the equivalent capacity of the diode in the camera tube. The most direct way of achieving the increased capacity without changing the diode geometry is the use of N^2 times higher conductivity in the n-type silicon substrate than might be desirable for conventional camera use.

The thickness and resistivity of the resistive sea is arranged to allow negligible leakage from one diode to the next during the 1/30 second between scans of the reading beam. Thus the lateral or spreading resistance of the film will be ignored as well as the shunt capacity. This considerably simplifies the discussion. The leakage resistance R_f and film capacity C_f must have an RC time constant much less than the 1/30 second between successive scans of the beam, yet long compared with the approximately 10^{-7} second or less that the reading beam is incident on the diode. For this particular geometry the RC time constant is about equal to the dielectric relaxation time constant, $\rho\epsilon\epsilon_o$, of the film material (ρ is the resistivity, ϵ the dielectric constant and ϵ_o the permeability of free space). Assuming $\epsilon \approx 10$ and choosing $\rho\epsilon\epsilon_o \approx 5 \times 10^{-3}$ second yields $\rho \approx 6 \times 10^9$ Ω-cm.

The ratio of diode capacity to film capacity C_d/C_f should be about equal to $N - 1$, for reasons which will become clear shortly. Thus the film capacity should be about the same as that of the camera tube diode, 2×10^{-15} farads, requiring a film thickness of about 2 microns over the 8 micron diameter diodes. The sheet resistance of the film is about 3×10^{-13} ohms per square which for a 1/30 second frame is adequate to control surface charging without reducing resolution.

The substrate potential is held at V_T, the target bias supply voltage. In the absence of stored signal the reverse-bias voltage of the diode equals V_T, the voltage across the film is zero, and the surface potential of the film equals the cathode potential, that is, zero. Reading beam electrons incident on the surface have a landing efficiency of essentially zero and no further negative charging of the surface can occur.

Suppose now that writing beam electrons are incident on the substrate, producing hole-electron pairs and that a fixed fraction of these with total charge Q_o diffuse to the diode, discharging the diode by a voltage $\Delta V_o \approx Q_o/C_d$. The charge Q_o will be referred to as the signal charge and ΔV_o as the signal voltage. It is assumed for the purpose of discussion that $\Delta V_o \ll V_T$ so that the diode capacity C_d is constant and has a value appropriate to V_T. In practice the film surface has negligible capacitance to ground so that no displacement current need flow through the film capacitance when the interface potential rises and the voltage across the film therefore remains at zero. Thus the film surface is brought to a potential ΔV_o. The maximum value of ΔV_o is about 5 volts to avoid beam bending as in the camera tube.

When the reading beam comes to the diode, the surface of the film is charged down essentially to cathode potential. Thus the series combination of capacitors C_f and C_d is recharged by an amount ΔV_o, requiring that the reading electron beam place a charge on the film surface

$$\begin{aligned} \Delta Q_1 &= \Delta V_o/(1/C_d + 1/C_f) \\ &= Q_o/(1 + C_d/C_f). \end{aligned}$$

(The reading beam current is set at a value high enough to provide the charge, ΔQ_1, during the short reading time interval. During this interval, conduction current through the film is negligible compared with the displacement current.) The charge ΔQ_1 flows through the target resistor R_L producing an output voltage proportional to the signal charge Q_o. The signal charge stored in the diode capacitance, originally Q_o, is reduced by the amount ΔQ_1 to a value

$$Q_1 = Q_o/(1 + C_f/C_d).$$

The voltage across the diode, originally $V_T - \Delta V_o$, is now $V_T - \Delta V_o/(1 + C_f/C_d)$. The voltage across the film is $\Delta V_o/(1 + C_f/C_d)$ which, because of the short RC time constant of the film, decays to zero before the next return of the reading beam. The surface potential therefore achieves the value

$$\Delta V_1 = \Delta V_o/(1 + C_f/C_d)$$

as compared with to the original value ΔV_o immediately preceding the first read. The process is then repeated. At the nth reading after the original signal charge Q_o was established by the writing beam, the output voltage is proportional to

$$\Delta Q_n = Q_o/(1 + C_d/C_f)^n$$

and the film surface potential at the instant preceding the nth read is

$$\Delta V_n = \Delta V_o/(1 + C_f/C_d)^{n-1}.$$

Since by design C_f/C_d is uniform over the target, the relative gray scale is preserved, the output signal is linearly proportional to the input signal and the output signal decays from one read to the next in a well-defined exponential fashion. The exponential time constant is

$$\tau = \tau_f(1 + C_d/C_f)$$

in which τ_f is the reading frame time. Thus for a compression ratio of N an appropriate value might be $C_d/C_f = N - 1$ which implies that the signal decays to $1/e$ in one writing frame time. For this case $\Delta Q_1 = Q_o/N$ which establishes that the signal level is the same as that in the camera tube. Since $\Delta Q_1/\Delta V_o = C_f(N - 1)/N$ this establishes the correctness of the choice of C_f about equal to the capacity of the camera tube diode (at least for $N \gg 1$).

Incidentally, in the camera tube and in many other applications, it is desirable to read virtually all of the signal stored in the diode on the first read (that is, one wants $N = 1$). This is accomplished by making C_d/C_f as small as possible. Thus the film thickness in a low lag target should always be under 0.1 micron as compared with 2 microns in the scan converter example above.

III. EXPERIMENTAL RESULTS

Figure 5 shows the scan converter. The tube is two one-inch vidicon-type guns facing opposite sides of the diode array target. The reading gun has a close-spaced decelerating mesh, as required for good resolution, while the writing gun mesh has been spaced back about one inch. This space permits light to be directed onto the target for measurement of the collection efficiency for holes generated by photons as in a camera tube.

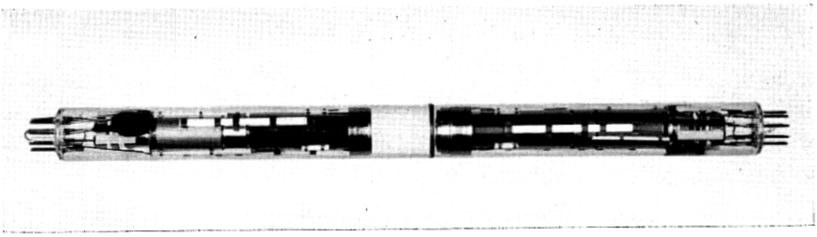

Fig. 5 — Scan converter. The diameter of the glass envelope is one inch. The large spacing allows optical measurements to be made on the target.

Most of the targets used to date are identical to those used in the camera tube; hence they have not been used for multiple readout. However, the validity of the capacitive subdivision of the available signal and the multiple read capability has been established with at least one target.

The resolution of the scan converter target is measured as follows. Both the writing gun and the reading gun are normally operated with magnetic deflection and focus. The writing beam current is modulated sinusoidally in time at frequencies locked to the horizontal scan rate producing a fixed sinusoidal charge pattern on the array. Feed-through is eliminated by adjusting the potential of the writing beam mesh as described earlier. The reading beam scanning rate is locked to that of the writing beam to avoid fluctuations in the relative number of reads per write. The reading beam scans over the fixed charge pattern producing a sinusoidal output signal. The measured peak-to-peak amplitude of the signal normalized to the value measured at low spatial frequencies is called the contrast ratio or modulation transfer function (MTF).

The MTF as a function of spatial frequency in cycles per inch of target is shown in Fig. 6 for a target with a substrate thickness of 20 microns and a diode spacing of 20 microns. Notice that the MTF is 55 per cent at 300 cycles per inch or 12 lines pairs per mm. The falloff may be attributed to four sources: (*i*) writing beam size, (*ii*) reading beam size, (*iii*) finite number of diodes, and (*iv*) lateral diffusion of holes. For the particular target the first two are least significant since under magnetic focus the reading beam is capable of resolving individual diodes and the writing beam has even greater resolving power. The third source of falloff may be appreciated by noticing that the linear diode density is 50 per mm, which means that there are about four diodes per spatial period at 12 cycles per

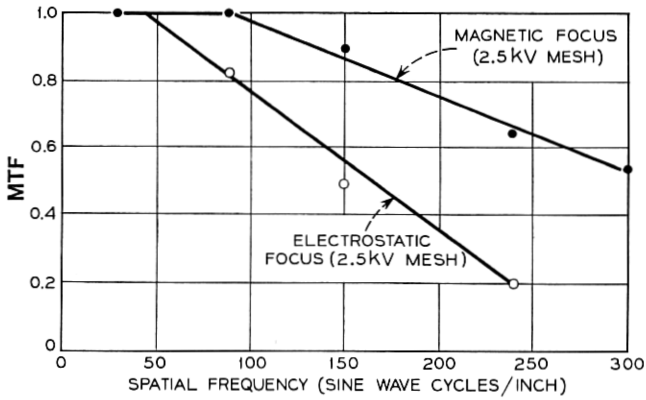

Fig. 6 — Measured modulation transfer function for the scan converter target.

mm. This is barely enough and a part of the falloff may be attributed to this fact.

Most of the falloff results from lateral diffusion of the holes which under the conditions of the measurement are produced within 1/10 micron of the substrate surface. Therefore, those that are collected must diffuse a distance of about 15-20 microns perpendicular to the surface. Since the lateral diffusion distance can be of the same order or greater, any detail requiring a spatial frequency of greater than 25 cycles per mm is effectively destroyed. The precise nature of the MTF falloff for the target depends on the target thickness, the diode geometry, and the volume recombination length and surface recombination velocity for holes. We plan a detailed discussion for a future paper.

The MTF at high spatial frequencies can be increased considerably by using thinner targets and increasing the diode density. Figure 2 illustrates a target with a substrate thickness of 10 microns and diode spacing of 15 microns corresponding to 67 diodes per mm. For this target the MTF is 100 per cent out to 280 cycles per inch and falls to 50 per cent at well over 400 cycles per inch. For this target the reading beam contributes substantially to the falloff in resolution.

The effective charge gain, of course, is a function of spatial frequency and its relative dependence on spatial frequency is the MTF shown in Fig. 6. However, the absolute charge gain for uniform storage patterns is a parameter of importance. Large values of gain are not really required or desirable for the scan converter; values of order 10 are useful. Values of order 10^3 or greater are desirable for some of the other applications.

The charge gain is measured in the following way. The unmodulated writing beam is scanned over some small area of the substrate at a current level sufficiently low that the resulting holes do not completely discharge the diodes. This can be checked by varying the writing beam current. The writing beam mesh is held negative relative to the substrate to suppress true low energy secondary electrons but not elastically reflected primaries. The redistributed secondary electrons, which land at much reduced energies compared with the primary beam, produce few, if any, hole-electron pairs. With the reading beam turned off, the current in the target lead measures the incident current in the writing beam that penetrates into the target. The charge gain in this case is effectively zero since the diodes are discharged and the hole-electron pairs are forced to recombine. The reading beam is turned on and scanned over an area which includes the area scanned by the writing beam. The increase in time average current measured in the target lead measures the arrival rate at the scanned diodes of all the holes generated in the substrate. The thermal part of the hole generation (the diode dark current) is determined by turning off the writing beam. The net current divided by the writing beam current penetrating the target is called the charge gain. A preliminary discussion of the expected results is appropriate at this point.

The charge gain should be describable by the expression

$$G(V) = \int_0^L \eta(x) \frac{dP(x, V)}{dx} dx \tag{1}$$

in which $\eta(x)$ is the probability that the hole, created at a distance x from the surface upon which the electrons are incident, will reach the diode space charge region and be collected, $dx(dP/dx)$ is the number of hole electron pairs created between x and $x + dx$ for an electron incident normally with kinetic energy V electron volts, and L is the substrate thickness. The function

$$P(V) = \int_0^\infty \frac{dP(x, V)}{dx} dx \tag{2}$$

which defines the total pair production per incident electron is given by

$$P(V) \approx V/3.5 \tag{3}$$

(corresponding to the fact that it takes on the average 3.5 eV to create one hole-electron pair). Writing

$$G(V) = P(V)\left[\int_0^L \eta(x)\,\frac{dP(x,\,V)}{dx}\,dx \Big/ \int_0^\infty \frac{dP(x,\,V)}{dx}\,dx\right] \tag{4}$$
$$= P(V)\boldsymbol{\eta}(V)$$

combines the effects of a variety of different phenomena into the function $\boldsymbol{\eta}(V)$ which will be called the effective collection efficiency.

A number of different target fabrication procedures have been studied to optimize the effective collection efficiency. The best to date is similar to that used for optimizing the sensitivity of the target for visible light and consists of a thin n^+ layer formed on the writing beam side of the target. The n^+ layer is formed by a shallow phosphorous diffusion into the n-type conductivity substrate. The effect of this layer is discussed a few paragraphs further on. The measured collection efficiency $\boldsymbol{\eta}(V) = 3.5G(V)/V$ as a function of electron energy is shown in Fig. 7. The collection efficiency approaches 0.5 for electron energies of order 10 KeV but falls well below 0.01 for energies below 2 KeV. Indeed in the energy range under 2 KeV the measured effective collection efficiency of a target for which the phosphorous diffusion was eliminated (the surface was merely etched) was higher at a constant value of 0.016.

An understanding of the measurements requires a knowledge of $\eta(x)$. However, a theoretical evaluation of $\boldsymbol{\eta}(V)$ is complicated by the fact that $dP(x,\,V)/dx$ is not negligible very close to the surface and $\eta(x)$ near the surface is strongly dependent on the surface properties of the silicon crystal. Aside from the surface complication $\eta(x)$ may be accurately

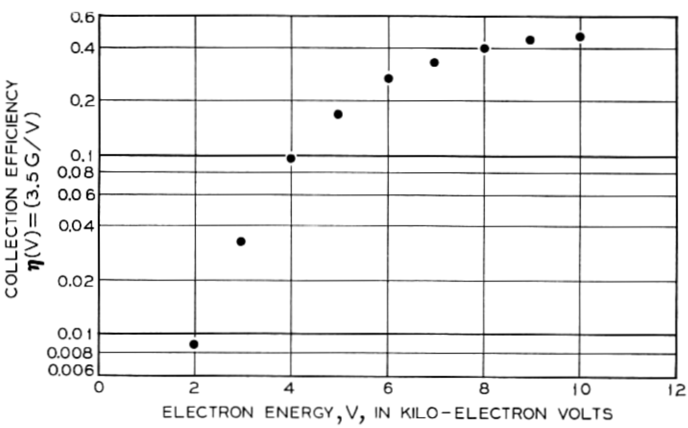

Fig. 7 — Measured effective collection efficiency for holes created by electrons of incident electron energy V. The effective collection efficiency $\boldsymbol{\eta}(V)$ is determined from the measured charge gain $G(V)$ by the relation $\eta(V) = 3.5G(V)/V$.

evaluated on the basis of a model in which only the bulk recombination lifetime τ, the surface recombination velocity S at $x = 0$, the diffusion coefficient D, all for the minority carrier hole, and the substrate thickness L are relevant,

$$\eta(x) = \frac{\sinh(x/l) + (D/lS)\cosh(x/l)}{\sinh(L/l) + (D/lS)\cosh(L/l)}$$
$$l = (D\tau)^{\frac{1}{2}}, \tag{5}$$

which follows from a one-dimensional Green's function solution of the diffusion equation for excess holes. In fact (1) might be considered to be the normalized Green's function solution for hole current through the plane at $x = L$.

Quite generally $\eta(x)$ increases with increasing recombination length l and the target fabrication is optimized to make l as large as possible. Typically $l \gg L$ and it is appropriate to make this assumption. Thus (5) becomes

$$\eta(x) \approx \frac{1 + Sx/D}{1 + SL/D}. \tag{6}$$

For an etched silicon surface $S \approx 10^6$cm per second while $D = 10$ cm^2 per second. Thus for $L = 10$ microns, which represents a minimum practical value, $SL/D \approx 10^2$. It can be appreciated that $\eta(x)$ will be quite small for $x \ll L$ unless S is substantially reduced. Thus for low beam energies corresponding to small penetration depths $\mathfrak{n}(V) \approx \eta(0) = (1 + SL/D)^{-1} \approx 10^{-2}$ which is consistent with measurements on etched targets. As mentioned above, the most relevant technique among those that have been tried to reduce S for this application is a shallow phosphorous diffusion into the surface upon which the electrons are incident. This produces an n^+ layer which repels holes diffusing toward the surface resulting in an effective value of $S \approx 10^3$cm per second. As a result the x-dependence in (6) is relatively small. Unfortunately the phosphorous diffusion drastically increases the recombination rate of holes in the n^+ layer and the layer can be characterized as dead. As a result $\eta(x)$ is not well known for very small x.

The uncertainty in interpretation of the experimental results introduced by the dead layer makes it desirable to study also the collection efficiency for holes produced by incident photons. For this case the initial distribution of holes created by the photons is accurately known. A corresponding effective collection efficiency function $\mathfrak{n}(\lambda)$ can be defined for pair production by photons of wavelength λ,

$$\mathfrak{n}(\lambda) = \frac{\int_0^L \eta(x)\alpha e^{-\alpha x}\,dx}{\int_0^\infty \alpha e^{-\alpha x}\,dx} = \int_0^L \eta(x)\alpha e^{-\alpha x}\,dx \tag{7}$$

in which $\alpha(\lambda)$ is the absorption coefficient for photons of wavelength λ. This formulation is not strictly correct for $\alpha L < 1$ since light penetrating to the surface at $x = L$ may be reflected back into the substrate. Also the distance L is not well defined because of the diodes. If it is assumed that within the dead layer of thickness δ, $\eta(x) = 0$ and beyond the dead layer $\eta(x)$ is given by the equation in (6) with x measured from the edge of the dead layer, then for $\alpha L \gg 1$

$$\mathfrak{n}(\lambda) \approx \int_\delta^\infty \eta(x - \delta)\alpha e^{-\alpha x}\,dx$$

$$\mathfrak{n}(\lambda) \approx \left[\frac{1 + S/\alpha D}{1 + SL/D}\right] \exp - \alpha\delta. \tag{8}$$

The measured collection efficiency as a function of wavelength (for the same target used for obtaining the data of Fig. 7) is shown in Fig. 8. The data were obtained by admitting light onto the target through the glass wall of the tube envelope. The data are corrected for Fresnel reflection losses at the glass surfaces and from the silicon. Curves of (8) with $S = 1.1 \times 10^4$ cm per second, $D = 10$ cm^2 per second, $L = 20$

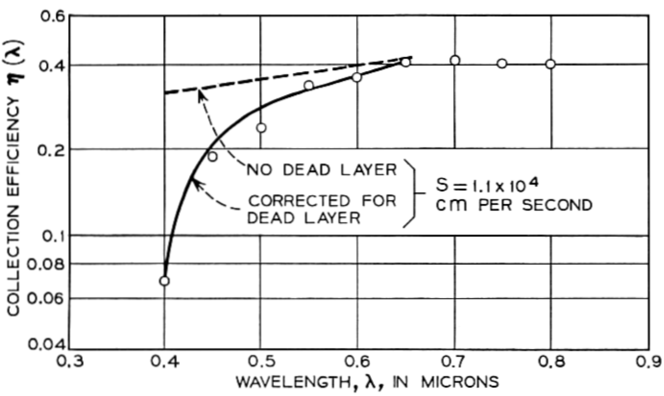

Fig. 8 — The measured collection efficiency for holes created by photons of wavelength λ. The solid and dashed curves were computed from equation (8).

microns and $\delta = 0$ and 0.21 microns are also shown. The calculation is not carried beyond $\lambda = 0.65$ microns since for longer wavelengths the target does not absorb all of the light transmitted past the surface. In fact, the slight falloff in collection efficiency above 0.7 microns may be attributed to this. Notice the good agreement with the curve corresponding to $\delta = 0.21$ microns indicating the approximate validity of the simple model of the dead layer. The dead layer thickness corresponds roughly to the phosphorous diffusion depth.

In the range $0.4 < \lambda < 0.65$ microns the absorption depth for photons[8] corresponds very roughly to the penetration depth for electrons in the energy range $4 < V < 10$ KeV. The penetration depth increases monotonically with λ or V to a maximum value of a few microns. Although the distribution of created holes for any value of λ is not the same as the distribution for any value of V, it is not surprising that the range of measured values of $\mathbf{n}(\lambda)$ and $\mathbf{n}(V)$ are quite similar. In either case a reduction of S to 10^3 cm per second, which is the more typical value observed in camera tubes, would increase the collection efficiency to close to unity over most of the range. A shallower phosphorous diffusion would also improve matters for low V or λ.

To date the only feature of the target which causes some concern about its future applicability is a slight burn-in or aging phenomena associated with the writing beam. It shows up as a decrease in charge gain over very heavily scanned areas. The rate of aging increases with writing beam current. It is not yet known whether the aging effect saturates, or whether it even occurs at all for low writing beam currents typical of most applications. The aging may account for the larger values of S observed in these targets as compared with camera tube targets.[9]

IV. CONCLUSION

A charge storage target for low energy scanning beam readout has been described with respect to its ability to produce a video representation of an electron image. Measurements of resolution and charge gain have been described. The target has general application in devices requiring an electron-image-to-video transducer and in scan conversion devices.

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