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INTRODUCTION

X-rays are extremely important in nondestructive testing. However, since radiation damage may occur, particularly with organic and biological specimens, much time and effort has been spent attempting to increase the sensitivity of X-ray sensors so that the incident flux level could be reduced to medically acceptable levels. Photographic film being one of the most sensitive and inexpensive detectors is widely used but suffers from a considerable delay for processing and is difficult to use if a motion picture X-ray is desired.

It would seem that an X-ray sensitive television system would be ideal not only because of instant replay of X-ray data, but also since such a system allows the operator to be located at a safe distance from the radiation source. Some development work has been done on X-ray sensitive photoconductive targets for vidicon tubes but these lack fast response as the target material is unable to respond quickly to changes in X-ray intensity. The result is a relatively long persistence tube with a time constant on the order of a fraction of a second which limits the ability of this tube to record fast motion. Thus, what is needed is an X-ray sensitive television pickup tube which combines high sensitivity with fast response time. It was envisioned that the mosaic diode array vidicon tube would offer these possibilities.
The concept of the combination of the light sensitivity of the p-n junction with a vidicon type of image tube was developed by Renolds in 1951 for which a patent was issued in 1961. This device was developed at the Bell Telephone Laboratories in an effort to produce a rugged sensitive, hard service, image tube as a replacement for the rather delicate photoconductive vidicon tube. This new tube was to be used in their picture transmitting telephone or "Picturephone", which was under development.

Figure 1 illustrated the basic difference of the new device from the conventional vidicon tube where the light sensitive target of the standard tube is seen to be a continuous sheet of photoconductive material, whereas the target of the diode array tube is actually a "mosaic" of reversed biased diodes. This circuit is represented in Figure 2, where the electron beam is seen to perform the switching function so as to sample each diode in the array to obtain spatial information.

Although silicon p-n junction radiation detectors were in general use, and it had been established as early as 1953 that each

References are repeated at end of dissertation.


FIGURE 1. REPRESENTATION OF PHOTOCONDUCTIVE AND DIODE ARRAY VIDICON TUBES

FIGURE 2. MOSAIC DIODE ARRAY CIRCUIT REPRESENTATION
X-ray photon could produce a large number of electron-hole pairs in a semiconductor junction, so that a high quantum yield could be obtained, this fact was not immediately applied to the diode array vidicon until sometime later when its application to the diode array tube was recognized.

This work was undertaken to study the possible radiation sensitivity of the new image tube and if possible, by the application of well known solid-state radiation detector technology, produce a device which would be applicable in radiation imaging, particularly for x-rays of energy high enough for nondestructive testing. The development of a theoretical model by which engineering guidelines could be specified such that fabrication could be optimized in any given application was also of interest.

As a foundation for the development of the theoretical model, the basic interactions of X radiation with matter and with silicon in particular will be examined. The creation of electron-hole pairs in the semiconductor material will be seen to be related to a loss of kinetic energy by the electrons involved in the X-ray photon interactions and it will be established that at higher photon energies, the energetic electron range in the vidicon target material plays a crucial role in the device sensitivity. From an examination of silicon diode junction theory, the carrier generation rate will be related to the signal produced by the diode array in the vidicon tube for operation in both integrating and nonintegrating configurations.
CHAPTER I

INTERACTION OF X-RAYS WITH SEMICONDUCTOR TO PRODUCE ELECTRON-HOLE PAIRS

The interactions of X and γ radiation and elementary particles having kinetic energies sufficient to insure material penetration with materials have been given attention by atomic physicists since the discovery of these radiations at the turn of the century. Since that time a considerable body of data and theory has accumulated. In this chapter, the basic phenomena and electron producing interactions will be examined. A theory will be developed to describe the operation of the mosaic semiconductor diode-array vidicon tube by applying existing data and the theory of atomic physics to the new field of solid state imaging. New theory will be developed where necessary. The fundamental operation of the device will be divided into two basic image producing interactions: first, the interaction of the X or γ rays with the target material to produce energetic charged particles; second, the interaction of the energetic charged particles, usually electrons having kinetic energies on the order of that of the incident photon, with the target material to produce hole-electron pairs through ionization. In the next chapter, the interaction of these pairs with the semiconductor junction and associated electron scanning along with electronics to produce a video signal will be discussed.
The possibility of using silicon diode array tubes for other radiation will be briefly discussed and experimental results will be presented which demonstrate the sensitivity of the silicon diode mosaic array vidicon tube to penetrating X radiation.

The basic experiment in X-ray absorption is the passage of a collimated beam of X-rays through a foil of material. Unlike beams of charged particles, a truly exponential flux attenuation with material thickness is observed because the photons are either scattered or absorbed in a single event.\(^4\) A catalogue of all possible processes by which the photon electromagnetic field can interact with matter has been put forth by Fano and is summarized in Table 1.\(^5\) Although there are twelve possible combinations of Columns I and II, there are in general only three which are not negligible and are historically given the names photoelectric effect, Compton scattering, and pair production. In the first case, a photon of some energy \(h\nu\) is absorbed by an atom of the material and an electron, called a photo-electron to indicate its originating mechanism, is ejected with a kinetic energy equal to that of the incident photon minus the binding energy of the atomic orbital. In the second case, an atomic valence electron is ejected as well as a photon of reduced energy. In the last case, an electron-positron pair are created both of which share the excess energy of the incident photon (over creation energy).

---


TABLE 1. POSSIBLE INTERACTION PROCESSES OF PHOTONS WITH MATTER

Since the fractional decrease in X-ray intensity in passing through a homogeneous substance is proportional to X, the distance traveled, in differential form the expression can be written

\[- \frac{dI}{I} = \mu \, dx \]

(1.1)

where the proportionality constant, \( \mu \), is called the linear absorption coefficient. The radiation intensity, \( I_x \), as a function of distance into the material is obtained by integrating the above expression or

\[ I_x = I_o \, e^{-\mu x} \]

(1.2)

where \( I_o \) is the incident X-ray intensity. As \( \mu \) is proportional to the density of the material, \( \rho \), \( \mu/\rho \) is a constant independent of the state of the absorber, either solid, liquid or gas and is called the mass absorption coefficient. Thus,

\[ I_x = I_o \, e^{-(\mu/\rho)\rho x} \]

(1.3)

However, the mass absorption coefficient is normally a function of both the atomic number, \( Z \), and the wavelength, \( \lambda \), of the incident
radiation. Figure 3 from data given in Cullity shows the experimentally observed variation for some common semiconductor elements in the energy range of 5 to 20 KeV. Since many important semiconductor materials are compounds or mixtures of two or more elements, it is of interest to note that the mass absorption coefficient is given by

\[
\frac{\mu}{\rho}_{\text{TOTAL}} = w_1 \left( \frac{\mu_1}{\rho_1} \right) + w_2 \left( \frac{\mu_2}{\rho_2} \right) + \ldots \tag{1.4}
\]

where \( w_1, w_2, \text{etc.} \), are the fractional composition of the number of atoms of the various elements present.

Since there are two ways in which the stopping power of a foil to a collimated beam of X-rays is measured, to avoid confusion, it should be pointed out that the Total Linear Attenuation Coefficient is obtained by using only the flux that passes through a small aperture on the axis of the incident beam in the calculation. The Total Linear Absorption Coefficient is determined from all flux emanating from the foil. Thus, the first case counts any photons merely scattered as lost, while the second case represents a measure of the energy absorbed from the incident beam. Since second order interactions are negligibly small, the scattered photons do not contribute appreciably to the creation of hole-electron pairs. Thus, the attenuation coefficient is a measure of the number of photons interacting in the material to produce ionization.

Another consequence of the insignificance of second order interactions is that the three predominant conversion mechanisms can be considered statistically independent so that the probability of a photon traversing an absorber of thickness \( x \) is given by the simple product

\[
\rho = e^{-\gamma x} e^{-\sigma x} e^{-\kappa x} \tag{1.5}
\]
FIGURE 3. OBSERVED MASS ABSORPTION AS A FUNCTION OF INCIDENT WAVELENGTH (FROM DATA IN CULLITY, REFERENCE (14),)
where $\gamma$ is the photoelectric total linear absorption coefficient, 
$\sigma$ is the Compton total linear absorption coefficient, and $\mathcal{J}$
is the pair production total linear absorption coefficient. Thus,
\[ \mathcal{I} = \mathcal{I}_0 e^{-\left(\sigma + \gamma + \mathcal{J}\right) \chi} = \mathcal{I}_0 e^{-\mu \chi} \quad (1.6) \]

Where $\mu$ is the total linear absorption coefficient as given above.

In general, each of the three principle interactions are a function of both the incident photon energy and the $Z$ of the absorber. It is found that the photoelectric effect predominates at the lowest energies, while pair production begins to become important for energies over 1 MeV and the Compton interactions are most important for the intermediate range of energy. The relative importance of these effects can be observed from Figure 4. Here, the incident photon energy for which the number of Compton interactions equals the number of photoelectric interactions or the number of pair production interactions is shown as a function of absorber atomic number, $Z$.

![Figure 4. Photon energy at which interaction mechanism cross-over occurs as a function of material atomic number, Z (from Evans (4)).](chart.png)
The Photoelectric Effect

At the lowest photon energies, the photoelectric effect is the predominant X-ray interaction mechanism and even in the lighter elements such as silicon, it plays a considerable role for energies as high as those used in industrial nondestructive testing. While a photon cannot be totally absorbed by a free electron, total absorption can take place if the electron is initially bound. The tightest bound electrons have the highest probability of absorbing a photon and it is found experimentally that 80 percent of photoelectric absorption takes place in the K shell provided that the initial photon energies are much greater than the binding energy for that shell. It should be noted however, that while the absorption takes place in the K shell, the entire atom participates in the process.

The photoelectric mechanism involves an incident photon of energy $h\nu$ interacting with an atom of material to produce a photoelectron, at an angle $\theta$ with the direction of the incident beam, having an energy $T$ where

$$ T = h\nu - B_e $$

(1.7)

and $B_e$ is the binding energy of the ejected electron. The angle $\theta$ has been found to be a function of the incident photon energy, where the photoelectron tends to be ejected in the direction of the electric field vector of the incident photon, hence at right angles to the impinging flux for the usual TEM radiation. At higher energies, the angles tend to be more in the beam direction. The energy $T$ is independent of exit angle.
Unfortunately, an exact formal solution of the photoelectric effect is both difficult and tedious as it is necessary to apply the relativistic Dirac equation to a bound electronic state, but theoretical solutions have been obtained for the angular distribution of photoelectrons at a number of incident photon energies\(^6\) and appear to be in good agreement with experimental observations.\(^7\) The polar plot of Figure 5 obtained from these solutions shows the relative number of photoelectrons scattered into the region between a cone of angle \(\theta\) and one of angle \(\theta + d\theta\), as a function of \(\theta\). It is observed that the photoelectrons are in general forward scattered in a rather diffuse cone such that the mean scattering angle decreases with increasing incident photon energy.

The absolute probability that a photoelectric interaction will take place is described by the atomic cross section \(\gamma\) in \(\text{cm}^2/\text{atom}\) and is related to the linear absorption coefficient by the equation

\[
\gamma = \alpha N
\]  \hspace{1cm} (1.0)

Here \(N\) is the number of atoms/\(\text{cm}^3\) and the assumption is made that the incident photon energy is much greater than the K shell binding energy so that the absorption and attenuation coefficients can be considered

---


FIGURE 5. THE RELATIVE NUMBER OF PHOTOELECTRONS SCATTERED INTO THE VOLUME BETWEEN A CONE OF ANGLE $\theta$ AND ONE OF ANGLE $\theta + d\theta$ AS A FUNCTION OF $\theta$ (FROM EVANS (4),)
identical. The atomic cross section is a strong function of both \( Z \) and \( h/\nu \) and is given by Evans to vary approximately as

\[
\sigma \alpha \frac{Z^4}{(h/\nu)^3}
\]

(1.7)

Both exponents are experimentally observed to be noninteger where, for example, the power of \( Z \) varies from 4.05 at 100 KeV to 4.6 at 3 MeV. A fairly good theoretical expression for the photoelectric cross section has been obtained by the blending of three approximate solutions\(^8\) and is given in Figure 6.

\[\text{FIGURE 6. THEORETICAL PHOTOELECTRIC CROSS SECTION OBTAINED BY BLENDING THREE APPROXIMATE SOLUTIONS (8)}\]

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\(^8\) C. M. Davisson, and R. D. Evans, Op. Cit., p. 84.
Compton Scattering

At energies between 80 KeV and 15 MeV Compton scattering is a dominant mechanism for silicon. Unlike the photoelectric effect, scattering occurs with the loosely bound valence electrons which have a binding energy much smaller than the incident photon energy so that in the theory they are considered "free".

A Compton scattering consists of a photon of energy $h \nu$ interacting in some way with a free electron such that the Compton electrons "recoils" at some angle $\phi$ with a kinetic energy $E$ and a scattered photon of reduced energy is produced at some angle $\phi$. By conservation of momentum, the entire process must lie in a plane and it is easily shown that

$$\frac{\nu'}{\nu} = \frac{\nu - \nu'}{\nu} = \frac{\rho}{m_e c^2} \left( 1 - \cos \phi \right)$$  (1.10)

where $h \nu'$ and $\lambda'$ are the energy and wavelength respectively of the scattered photon, $m_e$ is the electronic mass, $c$ is the speed of light, and the angles are measured with respect to the incident beam. The incident photon wavelength is represented by $\lambda$, or

$$\frac{\nu'}{\nu} = \frac{1}{1 + \chi \left( 1 - \cos \phi \right)}$$  (1.11)

where

$$\chi \equiv \frac{h \nu}{m_e c^2}$$  (1.12)

The energy of the Compton electron is given by

$$E = h \nu - h \nu' = h \nu \frac{2 \chi \cos^2 \phi}{(1 + \chi)^2 - \chi^2 \cos^2 \phi}$$  (1.13)

This energy attains a maximum value for $\phi$ equal to zero or

$$E_{\text{max}} = \frac{h \nu}{1 + \frac{\chi}{2}} = \frac{(h \nu)^2}{h \nu + \frac{m_e c^2}{E}}$$  (1.14)
It is interesting to note that the Compton shift in wavelength at any particular angle is independent of the incident photon energy and further, although only loosely bound electrons are strongly involved. The total interaction probability depends upon the number of electrons per atom as well as the number of atoms per cm$^3$. If the total linear attenuation coefficient of one material of density $\rho$, atomic weight $A$, and atomic number $Z$ is known, that of another material can be found with the relation

$$\sigma_1 = \sigma_2 \frac{A_1 Z_1}{A_2 Z_2}$$

and it is the relative constancy of $Z/A$ for all elements that makes the mass attenuation coefficient nearly independent of the nature of the absorber for Compton scatters. Thus, air is observed to have nearly the same mass absorption coefficient as lead, so that the material density becomes the crucial variable at these energies.

As in the photoelectric effect, the Compton electrons will on the average be forward scattered in a diffuse cone shaped distribution. Since for each photon scattered into an angle between $\theta$ and $\theta + \mathrm{d}\theta$ there is an associated Compton electron scattered into an angle between $\phi$ and $\phi + \mathrm{d}\phi$ or a solid angle

$$\mathrm{d}N = 2\pi \sin \phi \, \mathrm{d}\phi$$

so that by equating the number of electrons and photons,

$$\frac{\mathrm{d}N}{\mathrm{d}\lambda'} = \frac{\mathrm{d}n}{\mathrm{d}\lambda} \frac{5/2}{5/2} \frac{\rho}{\sin \frac{\pi}{\lambda'}} \left( \frac{\nu}{\nu'} \right)^2 \left( \frac{\nu}{\nu'} - \sin^2 \frac{\pi}{\lambda'} \right) \frac{\sin \frac{\pi}{\lambda'}}{\lambda' \sin \phi} \, \mathrm{d}\phi$$

where $\nu'$ is the classical electron radius.
The Klein-Nishina differential cross section expression for nonpolarized radiation\(^{(9)}\) has been used. By application of the relation between the electron and photon scattering angles and a slight rearrangement of terms, the angular distribution of the Compton electrons can be obtained as

\[
\frac{d\sigma}{d\phi} = \frac{d\sigma}{d\omega} \frac{d\omega}{d\phi} 2\pi \sin \phi = \frac{e^2}{\beta} \left[ \frac{\nu'}{\nu} \right] \left( \frac{\nu'}{\nu'} + \frac{\nu}{\nu'} - \frac{e^2}{\beta} \right) \left( \frac{\nu'}{\nu^2} \right) \sin \phi \nonumber 
\]

This expression is plotted in Evans and is shown in Figure 7 for various values of incident photon energy. It is observed that the distribution of Compton electrons tends to be nearly hemispherical at low energies, and peaks more and more in a forward direction as the incident photon energy is increased.

The electronic energy as a function of ejection angle and photon energy is given by Equation (1.12). Figure 8 shows the percentage of photon energy transferred to the electron as a function of angle with incident photon energy as a parameter. Consideration of Figures 7 and 8 indicate that while few electrons are ejected at 0 degrees or with the maximum energy transfer, many are ejected at low angles with nearly the maximum value of energy transfer. The maximum percentage of energy transfer as a function of the incident photon energy has been plotted in Figure 9 and it is seen that in the crossover region where the cross sections for photoelectric and Compton interactions are equal, the Compton-electrons will be much less penetrating, due to their lower kinetic energy.

FIGURE 7. CROSS SECTION VS. SCATTERING ANGLE OF COMPTON ELECTRONS FOR 0.51 MeV, 1.2 MeV AND 2.76 MeV (9)

FIGURE 8. PERCENTAGE OF ENERGY TRANSFERRED TO THE COMPTON ELECTRON AS A FUNCTION OF ELECTRON SCATTERING ANGLE
Figure 9. The percentage of energy transferred to the Compton electron as a function of incident photon energy for scattering exactly forward.
Pair Production

Above 1 MeV a third mechanism, pair production, begins to take place. The incident photon is completely absorbed and an electron-positron pair whose total energy is just equal to $h\nu$ takes its place. Thus,

$$J(\nu) = (T_e + m_e c^2) + (T_p + m_p c^2) \quad (1.19)$$

where $T_e$ and $T_p$ are the kinetic energies of the respective particles and $m_e c^2$ is the electronic rest energy. The total kinetic energy of the two particles, is given by

$$E_k = T_e + T_p = J(\nu) - 2 m_e c^2 \quad (1.20)$$

It can be shown theoretically(10) that pair production cannot occur in empty space. To maintain conservation of momentum, a minimum impulse of $\Delta m c^2$ (corresponding to the momentum of a 200 KeV photon) must be given to a nearby nucleus.(11) As a result, both the angle and energy of the ejected particles are found to have a distribution due to the variation of energy supplied to the reacting field. Figure 10 from Spring shows the angular distribution obtained for pair-electrons with argon and nitrogen for 2.62 MeV incident photons and a mean scattering angle of about 20 degrees is observed.


Neglecting the slight asymmetry between the electron and positron average energy, the probability for a certain fraction of the total available kinetic energy to be found in one or the other of the two particles is given by Figure 11. It should be observed that at higher incident photon energies, it is more probable for one of the two particles to possess most of the available kinetic energy, while at lower energies it is more likely that the energy be equally shared. These curves are for lead, but the probabilities
Figure 11. Distribution of energy between pair partners (11).

Figure 12. The quantity $v = (T_e + m_o c^2)/\hbar$ plotted as a function of $q'$. (From Evans, (4),)
for other elements are quite similar, as the reaction takes place in the nuclear field requiring only a slight electronic screening correction at higher energies. (12)

If the percentage of available kinetic energy absorbed by one of the pair-produced particles is known, it is then possible to calculate the average angle of ejection (13) from the equation

$$\langle \theta \rangle = \frac{q'(h\nu, T_e, Z) m_e c^2}{h \nu} \left( \frac{h \nu}{m_e c^2} \right)$$

(1.21)

where $q'(h\nu, T_e, Z)$ is a complex function and is plotted in Figure 12. Crucial to this discussion is the observation that $q'$ and thus $\langle \theta \rangle$ is largest when the particle kinetic energy $T_e$ is the smallest and vice versa. Thus, the pair-electrons with the highest kinetic energy will tend to be the most forward scattered. For energies below about 10 MeV, the most probable configuration is nearly equal sharing of the available kinetic energy and $q'$ will assume values close to unity. The average scattering angle will be approximately given by

$$\langle \theta \rangle \approx \frac{m_e c^2}{h \nu} \left( \frac{h \nu}{m_e c^2} \right)$$

(1.22)

Values of $\langle \theta \rangle$ are less than 20 degrees for incident photon energies over 2 MeV.

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Vidicon Target X-ray Response

When X radiation passes through a semiconductor material, hole-electron pairs are produced, but not directly by the photons since they can only interact by the foregoing mechanisms. Rather, it is the kinetic energy of the energetic electrons (or positrons) produced in those photon interactions which lifts electrons from the valence band to the conduction band to form hole-electron pair charge carriers. The total number of carriers produced are thus, a function of both the number of photon interactions and the kinetic energy of the particles produced.

As indicated above, the total mass absorption coefficient or the total mass attenuation coefficient is formed by the sum of the various component mechanisms and Figure 13 gives a plot of the total as well as the component mechanisms for silicon. This figure was derived from a plot for aluminum in Evans\(^4\) corrected to silicon. The exponential decrease in X or \(\gamma\) radiation intensity in passage through a layer of silicon can be determined from this figure. Since in the usual mosaic vidicon arrangement, the electron beam contacts the diodes on one side of the target material, while the radiation is incident from the other side, the attenuation of the supporting target silicon must be considered. If the target were lapped very thin and mounted on another material such as Beryllium for support, then an additional plot for that material would have to be used. The advantage of such a configuration is that in the range of photoelectric interaction, Beryllium has a much lower cross section.
FIGURE 13. TOTAL AND COMPONENT MASS ABSORPTION AND MASS ATTENUATION COEFFICIENTS FOR SILICON (EXTRAPOLATED FROM EVANS (4)).
Viewed another way, the coefficients of Figure 13 can be used to calculate the difference between the entrance and exit flux of a silicon layer and thus determine the number of photons interacting in the region. The photoelectric component will give the number of photoelectric interactions, the Compton attenuation component given by the sum of the scattering and absorption curves shown in Figure 13 will give the number of Compton interactions. The pair component will give the number of pair interactions. Also, it will be shown later that the total attenuation coefficient does, in fact, give the total number of interactions of all kinds.

As a comparison, the same attenuation data is given for lead in Figure 14. Such data would be pertinent to the operation of a device such as the so-called Plumbicon tube, but since an oxide of lead is employed in that device, the lead coefficient must be weighted for oxygen as indicated in Equation (1.4) above for compounds. It should be observed that the principle differences in the absorption coefficients of lead and silicon are primarily due to the photoelectric cross section and of particular importance to device sensitivity is the placement of the k edge, which occurs at roughly 90 KeV in lead, and 2 KeV in silicon. For photon energies below the k edge, photoelectric absorption must take place in the L shell and because the L photoelectric cross section is much lower than the K cross section, the mass attenuation coefficient is considerably reduced. For this reason, a semiconductor such as InSb with a k edge
FIGURE 14. TOTAL AND COMPONENT MASS ABSORPTION AND MASS ATTENUATION COEFFICIENTS FOR LEAD (Evans (4),)
at roughly 30 keV\(^{(14)}\) is observed to have a higher mass absorption coefficient than lead although of one half the average atomic number. Moreover, as indicated above, for photon energies above the k edge, the kinetic energy of the photoelectron will be equal to the energy of the incident photon minus the k shell binding energy so that the kinetic energy available for semiconductor ionization becomes small for radiation with an energy near the k edge.

In order to develop a theory that will describe the vidicon target operation with reasonable engineering accuracy for a wide range of photon energies, it is necessary to consider in some detail the interaction of the electrons produced by the foregoing mechanisms with the semiconductor target. If a beam of monoenergetic electrons of energy E are incident upon a foil of material, the number observed to pass through the absorber as a function of foil thickness produce a plot as shown in the inset in Figure 15. Although this curve is observed to have a "tail", the linear extrapolation of the main body of the curve to the background is often taken as the distance into the material beyond which the electrons will not penetrate. This is defined as the range, \(R_0\), of the electrons of energy E in that material. Figure 15 gives the range calculated from relations in Evans for electrons with kinetic energies from 10 keV to 1 MeV.

FIGURE 15. ELECTRON RANGE AS A FUNCTION OF ELECTRON KINETIC ENERGY AND ABSORBER (FROM EVANS, (4), CHAPTER 21)
In the case of the detection of β-rays or the case where the energetic electrons have nearly the same energy as the incident photon, Figure 15 applies directly. Usually, the electrons will have only a percentage of the incident photon energy transferred to them which will be a function of both ejection angle and photon energy. Thus, for Compton electrons, Figure 15 must be combined with Figure 9 to determine electronic range as a function of incident photon energy. It should be pointed out, however, that Figure 9 represents the percentage of energy available to the electron for maximum energy transfer, but few are produced with maximum energy and such a combination represents the maximum penetration depth rather than the average limit of penetration which would be somewhat less. Similarly, in pair production, only the excess energy above the creation energy of the pair is available in a kinetic form, and in the lower range of energies of pair production, it was shown above that this kinetic energy tends on the average, to be nearly equally shared between the particles. From these considerations, the range of energetic electrons for each mechanism is plotted in Figure 16 as a function of incident photon energy as well as the mass attenuation coefficient for each mechanism. It should be observed that for 100 KeV photons, the photoelectric mass attenuation coefficient is about one tenth that of the Compton reaction but that the photoelectrons have fifteen times the range of the Compton electrons, indicating a greater penetrability and ionizing capacity. Depending upon the geometry, the Compton mechanism, though of greater cross section could be relatively ineffective in producing electron-hole carriers.
FIGURE 16. MASS ATTENUATION AND ELECTRONIC RANGE FOR PHOTOELECTRIC COMPTON AND PAIR INTERACTIONS, IN SILICON.
Further importance of the range-energy relation can be seen by examining the operation of a standard silicon nuclear radiation detector when used with \( \beta \)-radiation. These detectors consist of a single p-n junction or Schottky barrier in high resistivity silicon and are operated with the radiation incident upon the barrier or junction side of the device.

For two values of incident electron kinetic energy, Figure (15) shows the relative number of electrons producing a certain number of electron-hole carriers in the detector vs the relative number of pairs produced per incident electron. For the low energy case where nearly all of the incident electrons are stopped within the sensitive volume of the detector, it is observed that every electron produces about the same number of electron-hole pairs. As the \( \beta \) kinetic energy is raised, a low energy tail begins to appear indicating that some of the incident particles are not producing as many hole-electron pairs as the rest which indicates that some of the incident particles are passing out of the sensitive region of the detector before losing all of their energy. At still higher energies as shown in Figure 17 a secondary low energy peak appears, which corresponds to the incident electrons passing through the sensitive volume of the device with little or no deflection. The existence of such a peak stands as proof that the electrons need not be stopped within the detector to produce a usable signal.

FIGURE 17. THE RESPONSE OF A HIGH RESISTIVITY JUNCTION COUNTER TO MONOENERGETIC ELECTRONS (15)

The broadened nature of this secondary peak is due to the phenomena of "straggling". (16) This is a large statistical variation in the amount of energy lost and the angular deflection that occurs in individual collisions in the material. Such variations can be so great as to have an incident electron lose more than half its kinetic energy in a single collision. This loss explains the existence of the high energy peak at large numbers of pairs as electron. It should be emphasized that concepts such as range apply only on the average and that for energetic electrons there are always large variations about the mean.

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The calculation of the actual charge deposition due to the incident radiation is important to the determination of silicon mosaic diode array vidicon sensitivity. For the case of an energetic particle being stopped within the semiconducting material, it has been determined empirically (17) that the number of hole-electron pairs created is a function only of the kinetic energy of the incident particle and the material of which the detector is constructed and not of the particle nor of the type of detector used. For silicon, the number of pairs per charged particle is given by

\[ N = \frac{E}{3.6} \]  

where \( E \) is the kinetic energy of the incident particle in electron volts. A theoretical model has been developed by Shockley (18) which is in good agreement giving a value of 3.5 electron volts required for each electron-hole pair. Thus, each 50 KeV photo-electron stopping in the material would generate

\[ N_{50\text{keV}} = \frac{5.5 \times 10^3}{3.6} = 1.56 \times 10^{4} \text{ pairs/electron} \]  

Since the holes and electrons flow in opposite directions in the material, ignoring recombination, the net charge produced effective

\[ \text{(1.2.4)} \]


in producing a signal is due only to one or the other of the carriers or

\[ Q = \eta N = \frac{6.62 \times 10^{-19}}{3.6} \frac{E}{10^{-19}}(E) \text{electron per } \text{photon} \quad (1.25) \]

which in this case is the charge deposition per interacting 50 KeV photon.

A theoretical upper limit can be placed on the sensitivity of a silicon mosaic array target of a given thickness by assuming that all of the carriers produced within the target are collected. At energies such that the electronic range is much less than the target thickness, proportionately few energetic electrons will be ejected from the material. The number of carriers produced per energetic electron can be calculated from Equation (1.23). If the photoelectric effect is dominant, for energies well above the edge, the photo-electron energy can be assumed equal to the energy of the incident photon, \( h \). The number of energetic electrons produced in the material for a given photon flux can be calculated from the total linear attenuation coefficient since the difference between the incident and exit photon flux gives the number of interacting photons. If the incident flux is reduced to one photon per unit area, this calculation yields the average number of hole-electron pairs produced per photon. Such a calculation has been made by Chester et. al. (19) for targets from 1 to 50 mils thick and the results are shown in Figure 18. These authors have indi-

FIGURE 18. AVERAGE NUMBER OF ELECTRON-HOLE PAIRS PRODUCED PER INCIDENT X-RAY PHOTON AS A FUNCTION OF PHOTON ENERGY (19)
icated, however, that the highest energy portion of the plot may not be exactly correct as the Compton mechanism could be less effective in producing electron-hole pairs. Examination of Figure 9 indicates that provided the negligible range assumption is valid, the much lower kinetic energy of the Compton electrons would indeed result in fewer pairs generated per Compton than photoelectric interaction.

While Figure 18 could be corrected at higher energies by using the lower Compton energy from Figure 16, it would be instructive to include the effects of electron range. An electron passing through the vidicon target material will produce ionization along its path in the form of electron-hole pairs. These are produced rather uniformly along the particle trajectory until it has lost most of its energy, but as it comes to rest, proportionately more pairs are created. (20) Thus, if nearly all the electrons produced in or incident upon a semiconductor absorber pass through it, the number of carriers that these particles generate will be proportional to the thickness of material. This energy loss depends on the particle kinetic energy and is shown in Figure 19 for silicon as calculated by Weiss and Whatley (21) from data taken by Nelms (20). A scale has been added to


give the number of carrier-pairs produced per unit material thickness. From these data it is possible to compute the amount of charge deposited in a thickness equal to the electronic range and subtracting it from the total deposition as given by Equation (1.23). A theoretical simplification can be made by assuming that on the average, an energetic electron with energy $E$ will produce constant ionization as given by Figure 19 in the material to a depth equal to
the range with an impulse deposition at that depth calculated as indicated above. If the particles are stopped within the material, the total deposition can be calculated by Equation (1.23) above.

In order to calculate the total charge deposited in a target of finite thickness so that an upper limit can be placed on sensitivity, it is convenient to mentally divide the target into two regions. Figure 20 shows the regions. It is clear that those interactions which take place in region (A) will produce on the average energetic electrons which will deposit all of their energy in the material since the thickness of region (B) is assumed equal to the electronic range. Those interactions in region (B) will on the average produce energetic electrons which will leave the material after traveling a distance $d_j$ which is a function of the depth at which the electron begins its trajectory. Forward scattering of electrons has been assumed which will produce a conservative estimate of charge deposition.

FIGURE 20. DIVISION OF TARGET MATERIAL INTO TWO REGIONS FOR THE PURPOSE OF CALCULATING X-RAY RESPONSE
To calculate the number of holes produced as a result of interactions in region (A) but not deposited exclusively in (A), the number of interactions must be calculated from the difference between the incident and exit photon flux in the region. Thus,

\[
N_A = \frac{d\Phi_{\text{interactions}}}{d\Phi_{\text{incident}}} = I_o \left(1 - e^{-\mu(d-R)}\right)
\]

(1.26)

where \( I_o \) is the number of photon/cm²/sec and \( \mu \) is the total linear attenuation coefficient. Thus, for the case where only one photon interaction mechanism is dominant, the number of hole-electron pairs per incident photon due to region (A) will be given by

\[
N_A = \frac{(1 - e^{-\mu(d-R)})}{3.6} E_{\text{part}}
\]

(1.27)

where \( E_{\text{part}} \) is the average kinetic energy of the electrons produced by an incident photon of energy \( h \nu \).

The flux incident on region (B) is given by

\[
I_{\beta} = I_o e^{-\mu(d-R)}
\]

(1.28)

and any differential slice of width \( dx' \) at the position \( x' \) produces a number of energetic electrons \( dN \) given by

\[
dN = I_o e^{-\mu(d-R)} e^{-\mu x'} dx'
\]

(1.29)

or

\[
dN = I_o e^{-\mu(d+x'-R)} dx'
\]

(1.30)

The number of electron-hole pairs produced as a result of interaction in region (B) is a function of the various pathlengths, \( d \), that the particles must travel to leave the material and the energy function of Figure 19 which will be called \( S(E) \). Again, it will be assumed for the moment that only one photon interaction mechanism is dominant so that \( S(E) \) will be single-valued. Thus, the
number of hole-electron pairs/cm² sec dν due to interactions at
some position x' in a thickness dx' is given by
\[ dν = I_0 \mu e^{-\mu \left( d - R_0 + x' \right) \left( R_0 - x' \right) \frac{1}{S(E)}} \] (1.31)

The total number due to interaction in (B) will be given by
\[ ν_β = I_0 \mu S(E) \int_{R_0}^{R_0 + x'} e^{-\mu \left( d - R_0 + x' \right) \frac{1}{S(E)}} dx' \] (1.32)
or
\[ ν_β = I_0 \mu S(E) \left[ R_0 + \frac{1}{\mu} \left( e^{-\mu R_0} - 1 \right) \right] \] (1.33)

which, on a per photon basis, yields
\[ \frac{ν_β}{ν_λ} = e^{-\mu \left( d - R_0 \right) \frac{1}{S(E)}} \left[ R_0 + \frac{1}{\mu} \left( e^{-\mu R_0} - 1 \right) \right] \] (1.34)

Thus for the single mechanism case, the total number of pairs that
are produced in a target of given thickness are given by
\[ m_T = ν_μ + ν_β = \frac{1 - e^{-\mu \left( d - R_0 \right) \frac{1}{S(E)}}}{\frac{1}{3} e^{-\mu \left( d - R_0 \right) / S(E)}} + e^{-\mu \left( d - R_0 \right) / S(E) \left[ R_0 + \frac{1}{\mu} \left( e^{-\mu R_0} - 1 \right) \right] \] (1.35)

and is valid for all thicknesses, d, so long as the following condi­
tions are met:
\[ d - R_0 = d - R_0 \] for \[ d \geq R_0 \]
\[ d - R_0 = 0 \] if \[ d \leq R_0 \] (1.36)

The thin target high-energy case is of interest where \( d < R_0 \). Here,
\[ m_T = S(E) \left[ d + \frac{1}{\mu} \left( 1 - e^{-\mu d} + \frac{\mu^2 d^2}{2} + \cdots \right) \right] \] (1.37)

If \( \mu d \) is less than 1,
\[ m_T \leq S(E) \left( \frac{\mu d^2}{2} \right) \] (1.38)
or the target sensitivity is proportional to the square of its thick­
ness. The factor \( \mu d \) is small as may be seen from Figure 11; \( \frac{\mu d}{\rho} \)
is about 0.02 for energies above 100 KeV so that
\[ \mu \approx 0.05 \gamma \] (1.39)
or \( \mu d \) is much less than unity for any reasonable target thickness.
If more than one photon interaction mechanism is dominant, it becomes necessary to account for the difference in the kinetic energy imported by each interaction. It is observed from Figure 13 that it will be necessary to account for no more than two mechanisms for any given photon energy. As indicated above, the number of events in a material of thickness $d$ is given by the relation

$$N = \frac{d\varphi_{n, T}}{\cos^3 \theta} = I_0 \left( 1 - e^{-\sigma d - \gamma d - \eta_d} \right)$$  \hspace{1cm} (1.40)$$

so that the ratio of photon to Compton electrons produced in a differential slice $dx$ is given by

$$\frac{dN_{\text{ph, tot}}}{dN_{\text{com, tot}}} = \frac{\gamma}{\sigma}$$ \hspace{1cm} (1.41)$$

The total production, however, must be given by the sum as

$$dN_{\text{tot}} = dN_{\text{ph, tot}} + dN_{\text{com, tot}}$$ \hspace{1cm} (1.42)$$

Thus,

$$dN_{\text{ph, tot}} = \frac{dN_{\text{ph, tot}}}{1 + \frac{\gamma}{\sigma}} \quad ; \quad dN_{\text{com, tot}} = \frac{dN_{\text{com, tot}}}{1 + \frac{\gamma}{\sigma}}$$ \hspace{1cm} (1.43)$$

and by integration of these expressions, it can be found that the number of photoelectric and Compton interactions which occur in a slice of material of thickness $x_0$ from an incident photon flux $I_0$ are given respectively by

$$N_{\text{ph, tot}} = I_0 \frac{1 - e^{-(\gamma + \sigma)x_0}}{1 + \frac{\gamma}{\sigma}} \quad ; \quad N_{\text{com, tot}} = I_0 \frac{1 - e^{-(\gamma + \sigma)x_0}}{1 + \frac{\gamma}{\sigma}}$$ \hspace{1cm} (1.44)$$

Each mechanism will have a characteristic average electron kinetic energy and therefore an associated electron range. These respective energies and thus, the respective electron ranges will not in general be identical so that the division of the target for calculation pur-
poses will have to be done separately for each mechanism. The situation is shown in Figure 21 where \( R_p \) and \( R_c \) are the respective electronic ranges, regions \( I_p \) and \( I_c \) correspond to (A) in Figure 20 for each interaction while \( II_p \) and \( II_c \) correspond to region (B) of Figure 20.

\[
\begin{align*}
\text{FIGURE 21. DIVISION OF TARGET FOR SENSITIVITY} \\
\text{CALCULATION IN THE CASE OF TWO} \\
\text{SIGNIFICANT PHOTON INTERACTION} \\
\text{MECHANISMS}
\end{align*}
\]

Proceeding as in the single interaction case above, it is calculated that the total number of holes per photon produced by photo interaction in region \( I_p \) and by Compton interaction in \( I_c \) is given by

\[
P_x = \frac{1 - e^{-\mu_1(d-n_p)}}{(1 + \frac{\mu_1}{E_f}) \gamma \varepsilon} E_{ph} + \frac{1 - e^{-\mu_2(d-n_c)}}{(1 + \frac{\mu_2}{E_c}) \gamma \varepsilon} E_{com} 
\]

In a similar manner it can be found that the number of holes per photon produced on the average in regions \( II_p \) and \( II_c \) is given by

\[
P_{II} = e^{-\mu_1(d-n_p)} S(E_{ph,II}) \left\{ n_p + \frac{1}{\mu_1} \left( e^{-\mu_1 n_p} - 1 \right) \right\} + \\
e^{-\mu_2(d-n_c)} S(E_{com,II}) \left\{ n_c + \frac{1}{\mu_2} \left( e^{-\mu_2 n_c} - 1 \right) \right\} 
\]
Thus, the total number of holes produced in the target is given by

\[ P_{\text{Total}} = P_T + P_E \]  

(4.47)

It is observed that this complicated expression for the target sensitivity reduces to the form of Equation (2.35) for a single photon interaction mechanism, if one of the cross sections is assumed to be zero. A computer program was written to calculate the number of holes per photon produced in silicon targets of various thicknesses according to the above theory for the energy range of 10 KeV to 4 MeV. The results in Figure 22 are comparable for Figure 18 and represent a theoretical limit to the obtainable target sensitivity which would always be reduced in practice by surface effects, finite depletion width, and recombination during diffusion in the field free regions, but enhanced by electron scattering.

It is useful to determine how the carriers created by the radiation are distributed as a function of distance in the material since the width of the dead layer of target material could play a significant role in the sensitivity of the device. An idea of the charge distribution produced in a silicon target of given thickness can be obtained by use of the approximation that the energetic electron deposits a certain amount of ionization charge along its path with the remaining charge being deposited in a relatively narrow region as the electron comes to rest. If the charge created along a pathlength equal to the electronic range for various electron energies is calculated by means of Figure 19 and Figure 15, it is found that for electron kinetic energies in the range of 10 KeV to 1 MeV approximately one half the available
FIGURE 22. AVERAGE NUMBER OF ELECTRON-HOLE PAIRS DEPOSITED PER X-RAY PHOTON FOR TARGETS OF VARIOUS THICKNESS AS A FUNCTION OF INCIDENT X-RAY ENERGY
ionization occurs as the electron comes to rest. For energies above 1 MeV, less ionization occurs at the end of the path. However, the charge at the end of the path is not deposited in a quantized lump, but is spread over a relatively broad region so that the following solution should indicate the general character of the distribution and not its exact shape.

For an X-ray flux incident upon the target material, from the -x direction, assuming forward scattering, no end of the path charge will be created for depths less than the electronic range. In the electronic range region, the density of holes produced in a slice of thickness Δx at a position x<R is proportional to the number of paths crossing the slice. Stated another way, the density of holes is proportional to the number of interactions produced within the target up to the position X to x < R. Thus, in one dimension for the remainder of the target,

\[ \text{Number in } \Delta x = \int_{0}^{x} \mathcal{I} \cdot S(E) \varepsilon^{\mu x'} \mu \Delta x' \Delta x = \mathcal{I} \cdot (1 - \varepsilon^L) \delta(E) \Delta x \quad (1.48) \]

where as μx is small, or on a per photon basis,

\[ \text{Number in } \Delta x \text{/ photon} = \mu \cdot S(E) \Delta x \quad x < R. \quad (1.49) \]

For depths x > R and negligible absorption, the number of paths crossing a slice will be independent of position so that the portion of the distribution due to charge created along the path is given by

\[ \text{Number in } \Delta x \text{/ photon} = \mu \cdot R \cdot S(E) \Delta x \quad x > R. \quad (1.50) \]

But also in this region, the end of path charge will be deposited so that for energies below 1 MeV the charge created for depths greater than the electronic range will be given by
In the case of two photon interaction mechanisms, the respective electron energies and ranges would be used with each resultant distribution weighted according to the mechanism cross section where the sum would give the distribution of ionization within the target. As an example, the distribution obtained for 100 KeV incident photons is shown in Figure 23. The smoothed response gives some indication of the expected behavior of a real target with statistical fluctuations.

\[
\text{Number in } \Delta x / (\phi \delta E) \int_{R_0}^{R} = \int_{R_0}^{R} \epsilon(E) \Delta x \chi \chi > R_0
\]

(1.51)

FIGURE 23. CHARGE DEPOSITION CALCULATION AS A FUNCTION OF DISTANCE INTO THE TARGET MATERIAL
Since the charge produced in the region near the surface is much less than that produced deeper into the material, it would appear beneficial to allow for a "dead layer" equal in thickness at least to the electronic range. This also helps to explain why the thin target optical tubes used at Bell Telephone Laboratories in early X-ray sensitivity experiments led them to believe that high energy response was not practical.\(^{(23)}\) While absorption was not considered in the above development, if the target were very thick, the charge distribution would taper off exponentially with distance.

While the effect of semiconductor properties on target response will be considered in detail later, it is necessary to observe at this point that the signal obtained from the target is due both to carriers generated within the depletion region as well as those which diffuse to it from within a diffusion length away as shown by McKay and McKafee.\(^{(24)}\) In the later case, the slope of the charge distribution becomes an important factor. From examination of Figure 23 it is clear that this diffusion region must be displaced from the surface to eliminate reduction in response due to the decreasing charge with distance toward the incident surface. This effect is further aggravated by a high recombination rate at the semiconductor surface which tends to reduce the minority collection from the generated charge distribution even more for small x.


Since the photo-electric cross section is very dependent upon atomic weight, at low energy, a thin layer of a heavier element deposited onto the silicon surface will inject electrons into the silicon creating ionization which will tend to compensate for the decreased charge density near the silicon surface. Care must be taken, however, to choose a material with a K edge sufficiently below the incident photon energy that the effect of increased cross section is not lost through insufficient energy transfer to the photo-electrons.

**Target Resolution With X-Radiation**

In addition to ionization distribution as a function of penetration into the target, the lateral distribution of carriers produced from the action of X-ray photons along a given axis is also important since this determines the maximum resolution of the device at a given photon energy. If for the moment, the diffusion of electron-hole pairs away from their point of creation is ignored, the average resolution obtained for the interaction of a large number of photons at a given point will always be less than or equal to the electronic range at that energy.

At low energies, since the photoelectrons tend to be ejected at relatively large angles and the energetic electrons suffer a large number of large angle collisions in a short distance, the result is a rather spherical ionization distribution with a mean radius about equal to the electronic range. At higher energies, as has been indicated above, the energetic electrons produced by all
three mechanisms tend to be ejected more forward and the scattering of these electrons in the material tends on the average to be produced more by a large number of small angle collisions. The net result is considerably greater resolution than might be predicted from the range-energy relation in the case of thin targets.

It can be shown that for a beam of monoenergetic electrons of energy $E$ incident in the $x$ direction upon an absorber of thickness $X$, under the assumptions of small angle deflections and thin material so that energy loss can be ignored, the density of the deflected particles as a function of position will be of the form

$$\psi(x, y) = \sqrt{\frac{2}{\pi}} \frac{1}{\Theta_0 x} \frac{e^{-\frac{3 \gamma^2}{2}}}{\Theta_0 x^2}$$

where $\Theta$ is the rate of change of the average angle of deflection with $x$ and is given by

$$\Theta = \frac{1}{16} \frac{\pi N}{A} \frac{Z^2}{\alpha} e^{\frac{1}{2}} \left( \frac{m_e c}{\rho} \right)^2 \left\{ \frac{1}{\ln \left( \frac{A}{\alpha} \right)} \right\}$$

Because of the approximate nature of the calculations,

$$\{ A \} = \left[ 1.96 \frac{Z}{A} ^{\frac{1}{2}} \left( \frac{m_e c}{\rho} \right)^{\frac{1}{2}} \right]$$

or

$$\{ A \} = \left[ \frac{1.37 \rho}{Z^2 \frac{m_e c}{\Theta}} \right]^{\frac{1}{2}}$$

whichever is smaller and where $A$ is the atomic weight, $Z$ is the atomic number, $\beta$ is the decimal percentage of the speed of light of the electron, $r_e$ is the classical electron radius, $m_e$ is the electronic rest mass, $p$ is the electron momentum, and $N$ is the density of scattering centers.

---

A narrow beam of electrons incident from \(-X\), upon a material produces a distribution of scattered electrons that is gaussian in the \(y, z\) plane which increases in width and decreases in magnitude for increasing penetration into the material so long as the material thickness is much less than the particle range. If, however, the vidicon target is to be used for the detection of \(X\)-rays rather than \(\beta\)-rays, the electrons will not be incident upon the target but will be produced within it. If the electrons produced at some point \(A\) in the material are considered, those ejected exactly forward will form a distribution as indicated above, while those ejected at some angle \(\theta\) will form a gaussian distribution in \(y'\) planes in a co-ordinate system rotated with respect for the forward direction by an angle \(\theta\). The situation is shown in Figure 24 and the total distribution for all angles at \(A\) measured at point \(P\) is given by the integral of all rotated gaussian functions of rotated planes passing through point \(P\) where their value is obtained by the transformation

\[
\chi' = x \cos \theta + y \sin \theta
\]

(1.56)

and

\[
y' = x \sin \theta - y \cos \theta
\]

(1.57)
Thus, if the particles produced at point A have an angular distribution $f(\theta)$, the total electron density at an arbitrary point $P$ is given by the integral

$$f(\alpha, \gamma) = \sqrt{\frac{3}{\pi}} \frac{1}{\theta_d} \int_{-\pi}^{\pi} f(\theta) \left( x \cos \theta - y \sin \theta \right)^{-\frac{1}{2}} \text{e}^{-\frac{1}{2} \frac{(x \sin \theta - y \cos \theta)^2}{(x \cos \theta + y \sin \theta)^2}} d\theta \quad (1.5+)$$
However, the electrons are not created at just one point, but are produced along the axis of the incident photon ray. Thus the above expression must be integrated with respect to \( x \) also to obtain the distribution in \( y \) at the depletion region, the half width of which would be a measure of the expected resolution. Therefore,

\[
\int f(y) = \sqrt{\frac{\pi}{\theta}} \int_0^\infty \int_0^\infty f(x) \left( \frac{\pi}{\theta} \right)^{\frac{3}{2}} e^{-\frac{x^2}{\theta^2}} \frac{\partial}{\partial y} \frac{\partial}{\partial x} f(x) \, dx \, dy
\]

(1.57)

gives the distribution at the depletion region where \( x_m \) is the thickness of material from the front surface of the target to the depletion region. Unfortunately, this integral has no simple analytical solution, but could be numerically integrated on a computer with any given set of conditions in a practical situation.

The variation of the gaussian half width as a function of material penetration is given from Equation (1.52) above as

\[
\theta_y = \frac{\theta_s}{\sqrt{3}} x^3
\]

(1.60)

For silicon, \( \theta_s \) is given by

\[
\theta_s \approx \frac{35}{E_{\text{esc}}} \ln \left( \frac{1.11 \times 10^2 E_{\text{esc}}}{10^7} \right) \text{ rad}
\]

(1.61)

so that the half width expressed as a function of electron kinetic energy in silicon becomes

\[
\theta_y \approx 345 \left[ \frac{E_{\text{esc}}}{E_{\text{esc}}} \right]^{\frac{3}{2}} x^3
\]

(1.62)

These solutions for several energies are shown in Figure 25. Since most of the energetic electrons at very high incident photon energies are ejected at angles less than 30 degrees, an approximation to the available resolution is given by

\[
R = 2 \left( \frac{d \sin 30'}{\theta_y} + \theta_y \right)
\]

(1.63)

where \( d \) is the target thickness. The factor of two is the result of
FIGURE 25. GAUSSIAN HALF WIDTH FOR SCATTERED ELECTRONS IN SILICA NEGLECTING ENERGY LOSS AND STRAGGLING.
the definition of resolution according to the Rayleigh criteria for two point sources.

It should be pointed out that the above calculations neglected the effects of carrier diffusion in the target material and that such diffusion could seriously degrade the resolution of the device. Thus, where high resolution at high energy is the primary objective, there would appear to be considerable advantage in using a fully depleted lithium drift target so that an electric field would exist over a considerable volume of the target to minimize the effects of diffusion.
CHAPTER II

INTERACTION OF INDUCED ELECTRON-HOLE PAIRS
TO PRODUCE A SIGNAL

Given the sensitivity of a semiconductor material to X or \( \gamma \) radiation, it is necessary to consider how such sensitivity can produce a signal in a vidicon tube. For most all practical applications the sensitive area of the vidicon target will be planar and located behind a lens for optical imaging or behind an object for radiation shadow-graphs. The most obvious method to obtain a spatial representation with an array of signal producing elements is to provide each with a connection to a representative signal controlled light source. However, such connections become difficult to construct if much information is to be transmitted and such a philosophy has only been reasonably successful in the case of fiber optics-channel-multiplier devices.

To make spatial information compatible with the cathode-ray tube displays, it is desirable to time-sequentially sample the signal producing elements by some geometrical scheme, with the sampled output being synchronously switched to the corresponding light sources of the display device. In commercial television systems, the scanning is done as one reads a book from left to right and from top to bottom, but such a system would not necessarily be optimum in all cases, particularly when the silicon mosaic diode
array vidicon tube is operated such that the sensitivity of the individual elements is proportional to the sample rate. Thus, if some of the elements were sampled more often than others, portions of the image field could be given more or less sensitivity as needed.

In regard to sensitivity with time-sequential switching, it is particularly desirable to have the unscanned elements active. Thus, each element can gather information between sampling times. Without this storage property, the sensitivity of the device is reduced by the inverse of the total number of elements in the array. If an array of semiconductor devices is to produce time-sequential spatial information, some means of connection to each element in turn must be provided and while such switching could be accomplished by means of a mechanical commutator for slow scan systems, at higher information rates some electrical means of switching is desirable. The switching function can be provided by digital logic in the form of a shift register, and several experimental "self-scan" units have been constructed using silicon and cadmium sulfide materials.\(^1\)\(^2\)\(^3\)


However, the large number of elements required to reproduce even a minimal television picture necessitated the use of large scale integration techniques to produce devices of usable size without excessive cost.

In television systems, an electron beam has been used to provide the switching function as well as to produce the signal and rapid switching speeds can be achieved with a relatively inexpensive device. However, such a switch has a relatively limited life compared to most solid state devices. The connections to the sensing elements can usually be made for only one direction of current flow (normally electrons from the cathode to the sensitive target), and there can be thermal noise generation due to the cathode temperature. Cathode noise has not usually been a limiting factor in existing devices, however.

Since the electron beam is a charge depositing mechanism, it limits the number of ways in which a semiconductor material can be used to produce a signal. Since a limited beam current is available for an electron beam of a given resolution the impedance of the signal producing elements must normally be kept quite high because the target elements themselves are required to possess storage, schemes

to increase the sensitivity through avalanche multiplication in the semiconductor target material\(^5\) where external storage would be necessary are excluded. The electron beam pickup tube does represent, however, a considerable economic advantage as well as an experimental expediency. This research will deal exclusively with electron beam switching and in particular with tubes of the vidicon type. The results could be generalized to other types of image tubes and the possibilities for hybrid, solid-state--vacuum tube imaging devices appear promising.

Before considering the mechanisms by which the target material produces a signal in the vidicon tube, a review of the structure of the standard photo-conductive device will be given. A typical structure with operating potentials is shown schematically in Figure 26 and includes a cathode, a grid for control of the beam current, an electrostatic focusing and acceleration region, a drift region where deflection is produced magnetically and a grid to provide a uniform deceleration field near the target. The target is maintained a little above the cathode potential.

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FIGURE 26. VIDICON STRUCTURE WITH OPERATING POTENTIAL

The literature on the subject of electron beam dynamics is extensive and that subject will not be considered here. Attention will be given to the interaction of the electron beam with the surface of the target and the conduction processes with the target by which the signal is produced. The target-electron-beam interaction is usually described as a charging of the target surface to cathode potential. The mechanism is not particularly simple, however, since it involves surface phenomena, which are not particularly well understood beyond an elementary level at this time. Also, a number of relatively uncontrollable parameters such as grain structure or surface contamination effect surface conditions.
A plot of the beam current versus the target potential obtained from one of the vidicon tubes used in these experiments is shown in Figure 27. A polished aluminum disk was placed at the target positron and a maximum beam current of a little over 1 microampere was obtained. Although the cathode was maintained at a potential of about +1 volt, no current is observed to flow for target potentials below approximately 2.5 volts.

Thus, a potential barrier of several volts must exist on the surface of the target material. This potential barrier is called the work function.\(^6\) The work function for aluminum is given as in

the range of 3 to 4 volts depending upon the surface condition of the crystalline regularity of the material\(^{(7)}\) and silicon is observed to have a similar value. The height of this surface barrier is lowered, however, by the presence of the decelerating field of the target mesh\(^{(8)}\). The field strength determined by the field mesh to target spacing could be a critical factor in obtaining operation at low target voltages.

It is seen that those electrons reaching the target at a potential of 2.5 volts were from the cathode with the highest kinetic energy and are just able to penetrate the surface barrier so that a small target current flows. As the target potential is raised, more and more electrons have kinetic energies greater than the work function when they reach the target so that the target current increases sharply with increasing target voltage. Eventually at some potential, all of the electrons reaching the target have kinetic energies greater than the material work function and the current more or less saturates with increasing target voltage. If the target potential is raised still higher, it is observed that the target current begins to fall and eventually drops to zero at about 26 volts. Although all of the electrons reaching the target are penetrating the surface barrier,

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this decrease in current can occur because other electrons are being
ejected as secondary emission, and every electron ejected from the
target material and collected by the field mesh represents charge sub­
tracted from the target current. When the secondary emission ratio
rises to unity, the target current drops to zero. Since the scanning
electron beam can inject a current into a semiconductor material,
discussion will now consider how such a current is capable of produc­
ing a signal from the radiation induced electron-hole pairs in the
target.

Diode Voltage Decay

Since the radiation produced electron-hole pairs in the
target are "free" carriers, one of the most straight-forward ways of
producing a signal would be by the conductivity modulation of the
material. For a semiconductor the conductivity is given by the
relation

\[ \sigma = q \left( \mu_e \left[ g \gamma + h_n \right] + \mu_h \left[ g \gamma + h_p \right] \right) \]

(2.1)

where \( \mu_h \) and \( \mu_e \) are the respective hole and electron mobilities,
\( h_n \) and \( h_p \) are the respective hole and electron equilibrium
concentrations, \( \gamma \) is the recombination lifetime, and \( g \) is the
generation rate of carriers by radiation. It is seen that the con­
ductivity is directly proportional to the radiation generation rate

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9 R. B. Adler, and R. L. Longini, SEEC-2: Introduction to
multiplied by the carrier lifetime plus an additive term. The dependence on lifetime indicates that room temperature silicon without the presence of traps would not be particularly effective in producing a signal. Cooling to liquid nitrogen temperature or the introduction of traps by gold doping could help to increase lifetime. Under penetrating radiation, the sensitivity of the entire volume of the material for carrier production could be utilized with fully depletion configurations, but the use of conductivity modulation in a vidicon tube is further restricted by the limited beam current which normally requires a resistivity of greater than $10^{12}$ ohm-cm.\(^{(10)}\)

The use of p-n junction arrays as suggested by Renolds\(^{(11)}\) and arrays of surface barrier blocking contacts as discussed by Heijne\(^{(12)}\), have several desirable properties as indicated by Crowell, et. al.\(^{(13)}\) These properties are:


\(^{11}\)Renolds, patent, Op. Cit.


(i) The dark current or radiation induced current can be independent of the target voltage.

(ii) The output can be linear with intensity.

(iii) The time constant can be much greater than that determined by the dielectric relaxation time of the material.

(iv) Wide visible and infrared spectral response as well as sensitivity to X and radiation over a wide range of energies.

(v) No burn-in to either light radiation or the scanning electron beam.

(vi) No persistance due to photoconductive lag.

(vii) Long target life and comparatively good resistance to radiation damage.

From (i) above the simple capacitor-light dependent resistor model used for the standard photoconductive vidicon target element is not particularly usable. The voltage invariance of the signal current with target potential would indicate a current generator to be a more appropriate model for the light or radiation dependent element. Because the target elements are no longer bilateral, an ideal p-n junction is included as well as a junction capacitance which is a function of the voltage across the ideal junction. A constant geometrical capacitance is also included to account for any external capacity such as to the field mesh. Finally the inclusion of series and leakage resistance gives the
complete model for a target element\(^{(14)}\) which is shown in Figure 28.

FIGURE 28. p-n JUNCTION EQUIVALENT CIRCUIT

In operation, the capacitor storage element is charged to some potential \(V_0\) by the electron beam and while the beam is scanning other elements, the capacitor voltage then decays by thermal and radiation current generation as well as by current loss through the leakage resistance. While a detailed solution of the voltage decay with time would require the application of semiconductor junction theory, a certain amount of useful information can be obtained from a solution based on the above model, where the ideal diode will be assumed to have either an ideal abrupt junction or an ideal graded

juncture. The capacitance of the ideal abrupt junction is given by

$$C(v) = \frac{A}{2} \left( 2 \delta \epsilon N \right)^{1/2} \left( \gamma_0 - V - \gamma \right)^{3/2} \tag{2.2}$$

where $A$ is the junction area, $N$ is the impurity concentration in the base material (diffusion side of the junction is assumed to have a much greater impurity concentration), $\gamma_0$ is the junction contact potential, and $V$ is the voltage across the element. For an ideal graded junction, the capacitance is given by

$$C(v) = A \left( \frac{\gamma a e^2}{4 \pi} \right)^{1/2} \left( \gamma_0 - V \right)^{3/2} \tag{2.3}$$

where $a$ is the net doping gradient at the junction. These capacitance expressions for the incremental junction capacitance where

$$C(v) = \frac{d\varphi}{dv} \bigg|_{v} \tag{2.4}$$

so that the current entering or leaving the capacitor is given by

$$I = \frac{d\varphi}{dv} = \frac{d\int_{v}^{v(t)} dv}{dv} \left( \varphi(v) \varphi^2 \right) \frac{dv}{dv} \tag{2.5}$$

which is not the same (although it gives the same results) as solutions using the geometrical capacitance computed from the junction charge distribution where

$$I = \frac{d\varphi}{dt} = C(v) \frac{dv}{dt} + \nu(t) \frac{dC}{dt} \tag{2.6}$$

It should be mentioned that these two types of junctions are of practical interest since a graded junction is a good approximation to the doping profile obtained for junctions produced by low temperature-long time impurity diffusions while the abrupt junction case is closely approximated by high temperature-short time diffusion.

If the thermal or generation current is set equal to $I$, in Equation (2.5), a differential equation in $v$ and $t$ is obtained.
Wecker\(^{(15)}\) using Equation (2.3) and Equation (2.5) above obtained the result for the graded junction:

\[
(V - \xi) \frac{2}{3} \frac{d\nu}{d\xi} = -\frac{n_i}{\xi^{\frac{1}{2}}} \left( \frac{\nu \xi}{e} \right)^{\frac{1}{2}}
\]  

(2.7)

where \(n_i\) is the intrinsic concentration, \(T\) is the carrier lifetime in the depletion region, and \(v\) is equal to the band gap minus the applied reverse voltage. Integration of this equation gives an expression for the voltage decay of the target element in the case of no generation due to light or radiation, or

\[
(V(t) - \xi) = \left[ V_o \frac{\nu}{\xi} - \frac{n_i}{\xi^{\frac{1}{2}}} \left( \frac{\nu \xi}{e} \right)^{\frac{1}{2}} \right]^3
\]  

(2.8)

where \(V_o\) is the value of \(V\) at \(t = 0\). In exactly the same manner, an expression can be derived for the abrupt junction where

\[
\frac{n_i}{\xi^{\frac{1}{2}}} = \frac{1}{(V - \xi)} \frac{d(V - \xi)}{d\xi}
\]  

(2.9)

or

\[
(V(t) - \xi) = V_o e^{-\frac{n_i}{\xi^{\frac{1}{2}}} \xi}
\]  

(2.10)

The solutions are only good for \(V > 0\) however, because the forward resistance of the junction has not been included and are approximate in that leakage resistance has been regulated. Thus, because of the way in which the thermal current generation varies with the depletion width, the element voltage is seen to decay in the dark with a function somewhere between an exponential and a cubic, depending upon the doping gradient.

In the case of illuminated or irradiated material there is an additional current which flows due to those electron-hole pairs collected by the depletion region which consists of both those pairs generated within the space-charge layer and those which reach it by diffusion. Carriers a diffusion length from the junction have been observed to produce a measurable component of the total current.\(^{16}\)

Thus, as in the case of the mosaic array vidicon tube where the light or radiation is incident on the base material side of the junctions, the generated current may or may not vary with the depletion width depending upon the absorption coefficient of the target material and the relative width of the depletion layer compared to the diffusion length.

If there is uniform generation of carriers throughout the material and the material is at least a diffusion length thick and the space-charge layer is thin, little change with depletion width would be expected since most carriers are due to diffusion and those carrier diffusions to the junction would not vary appreciably with depletion width. On the other hand, for uniform generation in a target where the space charge layer is considerably wider than a diffusion length, most carriers are due to generation within the depletion region and a more or less linear dependence with space charge layer width would be expected. This simplest linear dependence for the graded diode would give a current generation with

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the same functional dependence as the depletion width or

$$\mathcal{I}_2 = A \frac{\kappa R}{(V - \gamma)} \left( \frac{1}{\kappa R} \right) \left( V - \gamma \right)^{1/2}$$  \quad (2.11)

where A is the area, R the radiation intensity, \( \kappa R \) the carrier charge generation rate, and \( I_p \) the current generated due only to radiation or light. Now the current equation becomes

$$\mathcal{I}_{\text{therm}} + \mathcal{I}_2 = - \sigma (V) \frac{dV}{dt}$$  \quad (2.12)

or

$$A \left( \frac{q \kappa R}{2} \right)^{1/2} \frac{d(V - \gamma)}{dt} = \frac{A \kappa R}{\gamma} \left( \frac{12 \varepsilon}{q} \right)^{1/2} \left( V - \gamma \right)^{1/2}$$

$$+ A (\kappa R) \left( V - \gamma \right)^{1/2} \quad (2.13)$$

or

$$\left( V - \gamma \right)^{1/2} \frac{d(V - \gamma)}{dt} = \frac{k \cdot \gamma}{2 \gamma} \left( \frac{q \kappa R}{2} \right)^{1/2} \left( \frac{12 \varepsilon}{q} \right)^{1/2} + \frac{h}{e} \left( \frac{12 \varepsilon}{q} \right)^{1/2} \quad (2.14)$$

Upon integration and application of the boundary conditions, (2.14) becomes

$$\left( V - \gamma \right) = \left[ V_0 \left( \frac{12 \varepsilon}{q} \right)^{1/2} + \frac{k \kappa R}{\gamma} \left( \frac{12 \varepsilon}{q} \right)^{1/2} \right] \quad (2.15)$$

Similarly for an abrupt junction, the current would be given by

$$\mathcal{I}_2 = (\kappa R) A \left( V - \gamma \right)^{1/2} \quad (2.16)$$

which in an exactly analogous manner yields the result

$$\left( V - \gamma \right) = V_0 \left( \frac{k \kappa R}{\gamma} + \frac{\kappa R}{\gamma} \right) \quad (2.17)$$

Thus, regarding the step junction as an example, in the absence of radiation the element voltages will decay with a time constant equal to the material lifetime multiplied by the ratio of
the impurity concentration in the base material to the intrinsic
carrier concentration, which for good 10 ohm-cm material, with a
500 sec lifetime would yield decay times on the order of 2 to 20
seconds. For decay in the presence of radiation, the decay time is
shortened and since the signal is the result of the difference in the
decay times between the dark and the radiation case, as long as the
decay time constant is longer than the frame time the signal will be
linear with radiation intensity. Both the dark time constant and the
generation time constant are functions of the base material impurity
concentrations, yielding longer times for lower resistivity material.
However, the dark time constant is the stronger function varying
directly with impurity level while the generation constant varies only
as the square root of doping.

For the case of radiation current generation which is
independent of the depletion width, Weckler[17] has obtained a
solution for the graded junction as a function of time in terms of
time where
\[ \tau = \frac{C}{n_i} \left( \frac{e \alpha^2}{144 \varepsilon} \right) \tau \left( \frac{1}{\tau} - (\nu - \tau)^2 \right) \]

\[ \frac{\gamma^2 a \cdot (\gamma R)}{3 n_i^2 \varepsilon} \ln \left[ \frac{n_i \gamma \left( \frac{12 \varepsilon \gamma}{a} \right)^2 \left( \nu - \tau \right)^2 + (\gamma R)}{n_i \gamma \left( \frac{12 \varepsilon \gamma}{a} \right)^2 \frac{1}{\tau} + (\gamma R)} \right] \]

\[ (2.18) \]

However, if generation current can be assumed to dominate as would be the case at large incident intensities, the

\[
\left( V^2 - \frac{q^2}{2} \right) = \left[ V_0^2 - \frac{q^2}{2} \left( kR \left( \frac{12}{8 \epsilon N} \right)^{\frac{1}{2}} \right) \right]^{\frac{3}{2}} \tag{2.17}
\]

 Likewise for an abrupt junction where the generation current is independent of the depletion width, neglecting the thermal generation,

\[
I = (kR) A = \frac{A}{2} \left( \frac{\epsilon_0 \epsilon N}{x} \right)^{\frac{1}{2}} (V - \bar{\nu}) \frac{dV}{dx} \tag{2.20}
\]

or

\[
(kR) = \frac{1}{\sqrt{2} \frac{\epsilon_0 \epsilon N}{x} \frac{d(V - \bar{\nu})}{dx}} \tag{2.21}
\]

If the substitution of \( x = \sqrt{V - \bar{\nu}} \) is made and the expression integrated, the result is

\[
\mathcal{X}(x) = \frac{-kR}{2 \sqrt{27 \epsilon \epsilon N}} \mathcal{X} + C
\]

which on resubstitution and application of the boundary condition yields,

\[
\left( V^2 - \frac{q^2}{2} \right) = \left[ \frac{-(kR)}{2 \sqrt{27 \epsilon \epsilon N}} \mathcal{X} + \sqrt{V} \right]^2 \tag{2.23}
\]

Thus, the increase in the doping gradient to a step function produces an increase in the power to which the linear function is raised from 3/2 to a quadratic. In either case it should be clear that the decay is linear if \( t \) is small and the time required for the voltage to decay to zero is given by setting the terms within the bracket equal to zero. The abrupt case, for example, yields

\[
\mathcal{X}_0 = \sqrt{\frac{27 \epsilon \epsilon N}{kR}} \tag{2.24}
\]
The highest generation current density that this particular target can maintain and still operate in the reverse bias storage mode is found if \( t_0 \) is set equal to the frame time of 1/30 sec for a material resistivity is 10 ohm-cm, and a of bias \( v_0 \) is 4 volts, the expression will yield the generation current of

\[
(KR) = \sqrt[1/3]{(4)(3.2) \times 10^{-17} \times (4.4) \times 10^{-12} \times 4 \times 1 \times 10^{22}}
\]

or

\[
(KR) = 2 \times 1.02 \times 10^{-7} \frac{A}{cm^2}
\]

In the case of infrared radiation where every photon can be assumed to produce an electron-hole pair, the saturation intensity of the tube would be about

\[
S_{sat \, Flux} \approx 2 \times 10^{12} \frac{P_{4.4}}{cm^2}
\]

In practice this figure would be higher due to losses in the target in the infrared case, but for X-or \( \gamma \)-rays, the figure could be much lower since each X-ray photon can generate a number of electron-hole pairs as shown in the preceding chapter.

As indicated previously, the above solutions do not apply for intensities greater than saturation or stated another way, for voltages less than zero because of the presence of the low forward junction resistance. It should be apparent that under uniform illumination for a sufficient time the junction voltage will decay to some steady-state value and this value will not be zero but a
voltage analogous to that which appears across an open circuited illuminated "sun cell" or p-n junction.

If the junction doping gradient is taken to be a step function, then the diode voltage-current transfer function is given by the relation

\[ I = I_o \left( e^{\frac{eV}{kT}} - 1 \right) - I_L \]  

where \( I \) is the photo-generation current, \( I_o \) is the thermal generation current, \( k \) is Boltzmann's constant and \( T \) is the absolute temperature. Under uniform illumination at equilibrium

\[ I_{short} = -I_L \]  

and the open circuit voltage can be found by setting \( I = 0 \), which at room temperature gives

\[ V_{open} = 0.0575 \log_e \left( \frac{I_L}{I_o} \right) \nu \]  

Thus under illumination with a sufficient decay time, it is seen that the mosaic diode array elements will decay to a voltage given by the above equation and it should be remembered that this voltage will be measured as negative with respect to the reverse bias charging potential.

**Majority Carrier Charge Storage**

At this point it is not at all clear if the diode array will be capable of producing a signal for illumination greater than the saturation level. However, there is a charge associated with the forward-biased, open-circuit voltage condition, but it cannot be calculated from the simplified circuit model. It will be necessary
to examine the charge storage in the semiconductor junction in
greater detail. In general the electron beam can be thought of as
a means of depositing a certain amount of charge into the semi-
conductor. This charge is part of that required for the junction
voltage to be changed from one potential to another, normally
the voltage to which it has decayed in a frame time is returned
to the fixed reverse bias potential. It is assumed here that the
electron beam is capable of returning the diode to full reverse
bias in the time available to sample it. Thus the average beam
current required for the case of radiation producing a uniform
white level is given by

$$I_{beam} = \left( \frac{ft}{N_0} \right) \frac{\Delta Q_{forward}}{R_{reverse}} \quad (2.31)$$

where $ft$ is the frame time, $N_0$ is the number of elements in the
array, and $\Delta Q$ is the charge required to return one diode to reverse
bias from the decay voltage produced by the given generation rate.

Consider the case of an ideal step function doping gradient
junction: The charge which flows when the potential across the
device is changed is due to both a change in the majority carrier
distribution near the space-charge layer as well as to a change in
the minority carrier distribution. Under the depletion approximation,
all the majority carriers are assumed depleted from the material up
to a distance $L_p$ from the junction in the p material and a distance
$L_n$ from the junction in the n material and assumed equal to the
equilibrium carrier concentration beyond that distance. These
distances are a function of doping level and junction voltage and
are given by \(^{(18)}\)

\[ L_p = \left[ \frac{2E}{\varepsilon N_a} \left( \alpha - \nu \right) \left( \frac{N_0}{N_a + N_0} \right) \right]^\frac{1}{2} \] (2.32)

and

\[ L_n = \left[ \frac{2E}{\varepsilon N_0} \left( \alpha - \nu \right) \left( \frac{N_+}{N_0 + N_+} \right) \right]^\frac{1}{2} \] (2.33)

where \( N_a \) is the acceptor concentration and \( N_d \) is the donor concentration. For reverse bias, the minority concentrations go to zero at the edge of the depletion region and a representation of the carrier concentrations on one side of the junction is shown in Figure 29. So long as the equilibrium minority concentration is much less than the majority carrier concentration, it is clear that in reverse bias the charge required to change the junction potential from \( V_1 \) to \( V_2 \) is given for the p side by

\[ \Delta Q_{V_1 \rightarrow V_2} = \left( L_p(V_1) - L_p(V_2) \right) e A N_+ \] (2.34)

Where \( A \) is the junction area.

\[ \text{---} \]

It is important to observe that an equal amount of charge is required by the n type material. This fact can easily be established by use of the relation \( \frac{\mathcal{L}_p}{\mathcal{L}_n} = \frac{N_p}{N_n} \) which holds for the junction.\[ \text{(2.35)} \]

Thus half the charge required to return the junction to the reference

\[ ^{19}\text{Ibid, p. 2-14.} \]
reverse bias potential is supplied by the vidicon electron beam,
while the other half is supplied by the target bias source and
appears as signal

Thus, combining Equation (2.34) and Equation (2.32),
\[ \Delta Q_{\text{h},j} = \left[ A \left( \frac{\epsilon}{N_n} \right) \right] \left[ \frac{2}{\epsilon N_n} - \frac{N_o}{N_n + N_o} \right] \left[ \left( \nu_r - \nu_f \right)^2 - \left( \nu_r - \nu_f \right)^2 \right] \] (2.37)

or
\[ \Delta Q_{\text{h},j} = A \left[ \frac{q^2 \epsilon}{N_o + N_n} \right] \left[ \sqrt{\nu_r - \nu_f} - \sqrt{\nu_r - \nu_f} \right] \] (2.37)

This result is valid as long as the depletion approximation holds
so that the solution should be good for reverse bias as well as
small forward bias. For diffused mosaic array diodes, it can
usually be assumed that the p material impurity concentration from
the diffusion will be much greater than the donor density in the
base, n-type material or

\[ \frac{1}{N_p} \gg \frac{1}{N_n} \] (2.38)

Therefore, Equation (2.37) becomes
\[ \Delta Q_{\text{h},j} = A \left[ \frac{q^2 \epsilon}{N_o + N_n} \right] \left[ \sqrt{\nu_r - \nu_f} - \sqrt{\nu_r - \nu_f} \right] \] (2.37)

For 10 ohm-cm material, the charge per unit area required to change
the junction potential from 0 to -25 volts is found to be

\[ 20 \text{ Ibid, p. 2-12.} \]
Also of interest is the function

\[ \gamma = \left( \sqrt{\gamma_0^2 - \gamma} - \sqrt{\gamma_0^2 - \gamma_0} \right) \]

Since for the case indicated above where the radiation generated rate of voltage decay in volts/sec is independent of the target potential, the sensitivity of the vidicon device is seen to vary as \( \gamma \) which is plotted in Figure 30 for two values of \( \Delta V = V_1 - V_0 \).

For simplicity \( \gamma_0 \) was taken in this figure to be equal to one volt. It is observed in this case that the device sensitivity decreases with increasing target voltage. For those cases, on the other hand, where the rate of voltage decay is a function of the target potential, it is observed that the rate of decay tends to increase with increasing target potential, thus tending to compensate for the effect of \( \gamma \) above.
The resistivity of the base material also has an effect on the sensitivity of the device, not only from the dependence of the available charge per unit area, but also from the decay time doping dependence. From the foregoing analysis it is possible to predict the utility of such devices as lithium-drifted high resistivity target elements and indicate the limits involved. This is of particular interest since such work is planned by Chester at Bell
Telephone Laboratories. (21) From Equation (2.39) above it is seen that the charge available for a signal decreases as the square root of material impurity concentration decreases, but from Equation (2.32), it is seen that with decreasing doping the depletion width only increases as the inverse square root of the impurity concentration. Thus, the increase in generation current from the increased depletion width, which is the primary reason for producing a drifted junction, is compensated by the decreased available charge for signal. In the case where the generation does not depend upon the depletion width, there would obviously be no point in using a high resistivity base material. In regard to the decay time, it is seen from Equation (2.17) that the radiation generated voltage decay decreases as the square root of the doping giving some gain in signal, but the thermal decay time decreases linearly with doping so that some means of increasing the carrier lifetime would have to be employed. In view of this, the fully depleted target elements do not appear very promising, except, perhaps where it is desirable to increase the scanning area and the decrease in storage charge density is offset by increased diode area.

Minority Carrier Charge Storage

While the signal in the reversed biased case is primarily due to the variations in the majority carrier distribution, if the diodes are allowed to decay under uniform illumination to a forward biased condition, the contribution from the minority carrier concentration variation can be significant. The excess electron concentration in the p material, for example, as a function of distance and voltage is given by the relation

\[ n(x) = n_e \left( e^{\frac{x}{K_F}} - 1 \right) e^{-x/L_n} \]  \hspace{1cm} (2.42)

where \( L_n \) is the diffusion length, \( N_o \) is the equilibrium minority carrier concentration and \( x \) is measured from the edge of the depletion region. Since the space charge width does not appreciably change with small forward bias voltage, the stored charge can be found by the integration of the above expression and the charge required by the minority distribution for a change in the junction potential from \( V_1 \) to \( V_2 \) is given by

\[ \Delta Q_{\text{Min}} = A \left( \int_{0}^{\infty} \left( e^{\frac{x}{K_F}} - 1 \right) e^{-x/L_n} dx \right) \]  \hspace{1cm} (2.43)

or

\[ \Delta Q_{\text{Min}} = A \left[ n_e L_n \left( e^{\frac{V_2}{K_F}} - e^{\frac{V_1}{K_F}} \right) \right] \]  \hspace{1cm} (2.44)

If \( V_2 \) is less than a few tenths of a volt (negative),
This charge represents a signal and is exactly that which gives rise to the finite switching time when a p-n junction diode goes from forward to reverse bias.\(^{(22)}\) The time dependence of the removal of this charge has been treated in some depth,\(^{(23)}(24)(25)\) but in the case of the vidicon mosaic array target, there is usually sufficient time while the electron beam is contacting the diode for both the removal of the excess minority carriers as well as to return the diode to the reference reverse bias voltage. Thus, the average target current for a uniform white level becomes

\[
\mathcal{I}_{\text{ave}} = \left( \frac{\tau}{\lambda} \right)^{-1} \left( \Delta Q_{n^0} + \Delta Q_{m^0} \right) \quad (2.46)
\]


The value of \( n_o \), in the absence of photo-generation is given by the expression

\[
\frac{n_o}{n_i} = \frac{N_i}{P_o}
\]

(2.47)

where \( P_o \) is the majority carrier concentration and \( n_i \) is the intrinsic carrier concentration. At room temperature \( N_i \) is approximately equal to \( 1.5 \times 10^{12}/m^3 \).

Since for an ideal diode,

\[
\frac{I}{I_o} = \left( e^{\frac{qV_T}{kT}} - 1 \right)
\]

(2.48)

the expression for the minority \( \Delta Q \) becomes

\[
\Delta Q_{n_o} = A N_o L_n \left[ 1 + \frac{I}{I_o} \right]
\]

(2.49)

where \( I \), the effective forward current, can be determined from the illuminated open circuit voltage or from the photo-current which is observed under constant voltage reverse biased conditions. The current, related to the open circuit voltage or \( \Delta Q \) to the generation rate as

\[
V_{oc} = \frac{q}{e} L_n \left[ 1 - G (L_n + L_p)/I_{eff} \right]
\]

(2.50)

where \( G \) is the electron-hole pair generation rate and \( L_n \) and \( L_p \) are the minority carrier diffusion lengths. Charge \( \Delta Q \) becomes

\[
\Delta Q_{n_o} = N_o A L_n \frac{q}{e} \left[ e^{(V_{oc}V_{n-o})/(kT)} L_n \left[ 1 + \frac{1}{e} \left( \frac{L_n + L_p}{I_{eff}} \right) \right] \right]
\]

(2.51)

by combining Equation (2.48) with Equation (2.50) to obtain \( \Delta Q \) in terms of the generation rate.
It is crucial to observe, however, that this value is no longer valid for pair generation beyond the thermal rate. The increased carrier production increases \( n \) in a manner similar to an increase in the temperature of the material. This can be shown by considering a material at some temperature \( T \) which provides a thermal generation rate \( g(T) \). For no incident radiation, at equilibrium \(^{26}\) where

\[
g(T) = R(T) = R(T) \, n \, p
\]

\( R(T) \) is the recombination rate, \( n \) and \( p \) are the majority and minority carrier concentrations and \( r(T) \) is the temperature dependent proportionality factor for bimolecular recombination. In the case of radiation or photon generation of electron-hole pairs, the expression becomes

\[
g(R) + g(T) = R(T) = n \, p \, r(T)
\]

where \( g(R) \) is the radiation pair generation rate and since the temperature dependence of the recombination rate is unchanged by the increased generation, the \( n \, p \) product must account for the addition

\[
g(R) + g(T) = R(T) = n \, p \, r(T)
\]

If \( g(R) \gg g(T) \)

\[
g(R) \approx R(T) \, n^2
\]

and for \( g(R) = 0 \),
\[
\frac{\mathcal{Q}(R)}{\mathcal{Q}(\tau)} = \frac{n_i^2}{n_e^2} = \frac{I}{I_e} \tag{2.56}
\]

Thus,
\[
\frac{\mathcal{Q}(R)}{\mathcal{Q}(\tau)} = \frac{n_i^2}{n_e^2} = \frac{I}{I_e} \tag{2.57}
\]

so that the minority concentration becomes
\[
n_e \approx \frac{n_i^2}{P_o} = \frac{n_i^2}{P_o} \left( \frac{I_e}{I_e} \right) \tag{2.58}
\]

and \( P_o \) is given by the material doping. Thus, \( \Delta Q \) can be written
\[
\Delta Q_{n: n} \approx \frac{1}{n_i} \left( \frac{n_i}{P_o} \right) \left( \frac{I_e}{I_e} \right)^2 \tag{2.59}
\]

Using the \( L_n \) of Equation (2.66) below, \( \Delta Q \) becomes
\[
\Delta Q_{n: n} \approx 1.0 R \times \epsilon \left( \frac{I_e}{I_e} \right)^2 \frac{1}{n_i} \tag{2.60}
\]

It is important to note that if these results are applied to experimental data that \( I_0 \) is the thermally generated current and any leakage resistance must be accounted for separately.

Considering the charge available due to change in the majority carrier concentration under reverse bias conditions, in Equation (2.40), majority and minority contributions will become equal for an effective forward current to dark current ratio on the order of \( 10^3 \). For a smooth transition between the reverse bias storage mode and the forward bias mode, it is necessary to have the voltage decay time equal the frame time for a radiation level giving equal majority and minority charge contributions. If the decay time is shorter than the frame time at this radiation level, the reverse bias mechanism
will saturate before the forward charge can take over and a dip in the intensity transfer function will occur. The overall character of a matched response curve would be a steep rise at low radiation intensities where storage occurs followed by a smooth transition to a lower gradient portion. Thus, using Equation (2.58), Equation (2.54) becomes

$$\Delta Q = A \frac{L_n}{g}\eta_e \left( \frac{g_{(F)}}{g_{(0)}} \right) \left[ 1 + \frac{g_{(F)}}{g_{(0)}} \left( \frac{L_n + L_p}{\tau} \right) \right] \quad (2.61)$$

Since the forward biased condition will only occur for intensities great enough to decay the diode voltage to equilibrium in less than a frame time,

$$g_{(F)} \left( \frac{L_n + L_p}{\tau} \right) \gg 1 \quad (2.62)$$

so that

$$\Delta Q_{n+} = A \frac{g^2}{\tau} \eta_e \left( \frac{g_{(F)}}{g_{(0)}} \right) \left( \frac{L_n - L_p}{\tau} \right) \quad (2.63)$$

and

$$\Delta Q_{n-} = A \frac{g^2}{\tau} \eta_e \left( \frac{g_{(F)}}{g_{(0)}} \right) \left( \frac{L_n + L_p}{\tau} \right) \quad (2.64)$$

The diffusion length in the above equations is given by

$$L_n = \sqrt{D_n \tau} \quad (2.65)$$

where $D_n$ is the electron diffusion constant and $\tau$ is the carrier lifetime. For $D_n = 25 \text{ cm/sec}$ and $\tau = 500 \times 10^{-6}$,

$$L_n \approx 1.1 \times 10^{-5} = 1.1 \text{ m} \quad (2.66)$$

which is, of course, the thickness of that portion of the sensitive volume of the target which is due to the diffusion of carriers in the base material.
Since $\ln G$ is a relatively slowly changing function compared to $G$, the high radiation intensity transfer function will also tend to be more or less linear. A typical output signal vs incident intensity characteristic is shown in Figure 31. This plot was obtained from one of the experimental mosaic diode array vidicons used in these experiments under uniform illumination and the results are clearly consistent with the above analysis.

For high intensity imaging, the use of high resistivity or lithium drifted material appears much more promising than for the reverse bias case, not only because a decrease in the doping level increases the signal charge, but also because the shortened decay time due to the higher resistivity material does not matter and in fact could be beneficial in establishing the necessary equilibrium conditions. Also, the lower doping would produce a wider depletion region which could increase the number of carriers collected although the space charge layer for a given material would certainly not be as wide as in the reverse bias case. The lack of storage decreases sensitivity. If some means of adding storage to this signal producing mechanism could be found, a device of considerably greater sensitivity could be produced.

If the electron beam current is limited, another restriction is placed on the mosaic vidicon in that only a certain amount of charge can be given to the target in a frame time. If the tube is to be operated only in a reverse bias storage mode, the maximum signal condition occurs for an all white picture where all the diodes decay to zero in $1/30$ second. Therefore, the total charge required is
FIGURE 31. RELATIVE VIDICON OUTPUT AS A FUNCTION OF INCIDENT INFRARED INTENSITY
\[ Q_{\text{rev}} = \Delta Q_{\text{rev}} (0 \rightarrow V) \propto D_R \]  \hspace{1cm} (2.67)

where \( V \) is the reverse bias potential, \( a \) is the target area swept, and \( D_R \) is the ratio of the diode total area to the total area or a measure of the active area. In terms of the beam current this becomes

\[ I_{\text{beam}} \left( \frac{1}{2} \right) = \Delta Q_{\text{rev}} (0 \rightarrow V) \propto D_R \]  \hspace{1cm} (2.68)

and for a standard television aspect ratio of 3:4, this equation be solved for the scan width or

\[ W_{\text{max}} = \left[ \frac{2}{\sqrt{2}} \frac{I_{\text{beam}}}{D_R} \right]^{\frac{1}{2}} \]  \hspace{1cm} (2.69)

In terms of the material parameters,

\[ W_{\text{max}} = \left[ \frac{2}{\sqrt{2}} \frac{I_{\text{beam}}}{D_R} \left( \sqrt{2} \frac{6}{5} \frac{135}{\mu\text{A/mm}^2} \right) \right]^{\frac{1}{2}} \]  \hspace{1cm} (2.70)

where for a beam of 1 microampere and \( \Delta Q \) of 135 picocoulomb/mm\(^2\) and \( D_R = 1 \),

\[ W_{\text{max}} = \left[ \frac{2 \times 10^{-9}}{\sqrt{2} \frac{6}{5} \frac{135}{\mu\text{A/mm}^2}} \right]^{\frac{1}{2}} \approx 1.8 \text{ cm}, \]  \hspace{1cm} (2.71)

It is interesting to observe that the maximum target sweep width is proportional to the fourth root of the doping level so that an increase from 10 ohm-cm to 1000 ohm-cm material only increases the allowable sweep width by about 3 times. If operation into the forward bias condition were desired also, then the charge required by the change in the minority carrier distribution would have to be added.
How small the imaging array can be made for optical applications with X or γ radiation or direct interaction with electrons in microscopy is of interest. The target structure with the diffused diodes and their associated depletion regions is shown schematically in Figure 32.

![Target Structure with Large Depletion Width](image)

**Figure 32. Target Structure with Large Depletion Width**

It may be seen that no matter how small the diffused diode areas are made, the resolution will never be greater than twice the depletion width. Further, since the depletion width is a function of diode voltage, it is possible that without sufficient spacing the space-charge regions of adjacent diodes can merge so
that the entire target becomes a blocking contact and the image is lost. From the depletion width nomograph of Appendix A, it is found that for 8 ohm-cm material biased at -10 volts, a dead region of 12 microns is needed between diodes. The effect of the merging of the space charge regions, according to Grove and Fitzgerald (27), has been used to explain the observed saturation at a bias of about 10 volts for targets having 8 micron diodes separated by 12 microns. Buck (28) has also observed the same saturation for .1 ohm-cm material and has indicated that the depletion region in this case seems to be generated by a surface effect. It would appear that surface phenomena tends to limit the interdiode spacing which can be used. However, it would appear that the narrow space charge region of the forward bias condition could yield a higher resolution target, but having less sensitivity than is possible for the reverse bias case. Such a trade off might be practical, however, and such a device would be highly useful in high voltage electron microscopy especially since the scan area can be increased, decreased, or moved about electronically with no burn-in on a diode array target.


It should be mentioned that p-n junction arrays can be fashioned by epitaxial growth or ion implantation as well as by diffusion but the Schottky barrier blocking arrays as suggested by Heijne (29) are of even greater interest. Such arrays have been constructed with integrated circuit techniques for use in digital logic, but do not seem to have been used for imaging purposes. These arrays were constructed by depositing aluminum through holes etched in an oxide mesh covering the silicon and had excellent characteristics as long as two conditions were met: first, use of N-type silicon with a doping level less than $10^{17}/\text{cm}^3$ (resistivity greater than .08 ohm-cm); and secondly, all operations subsequent to the deposition must be performed at a temperature less than 577° C, (the aluminum-silicon eutectic temperature). (30) The low temperature fabrication of these devices has the advantage that elimination of the high temperature diffusion will allow high quality material to retain its lifetime and thus produce arrays with long dark-decay rates. Other metals besides aluminum can be used to produce a barrier diode. Gold has been used with silicon for this purpose for some time in the production


of single diode radiation detectors.\(^{31}\) Aluminum would appear to be a slightly better choice because the gold evaporation tends to destroy the carrier lifetime in silicon if it begins to diffuse into the material with time and temperature.

It should be noted that the Schottky barrier is similar to the p-n junction in regard to its reverse bias characteristics but is different in forward conduction. When the barrier diodes are forward biased, so-called "hot" electrons are injected from the n material into the metal thermionically. "Hot" electron lifetime in the metal is \(10^4\) to \(10^7\) times shorter lifetimes in p-type material and since the n type material receives no minority carrier holes from the metal, such junctions are capable of being switched from forward to reverse bias in an extremely short time. For vidicon purposes there would be little or no charge deposition due to the minority carrier distribution and hence no contribution from the non-storage, forward conduction charge. Such a target would saturate at high intensities, the lone mechanism for modulating the beam current being the open circuit diode voltage. It is possible to produce hybrid diodes consisting of a Schottky barrier together with a diffused guard ring at the edge of the oxide hole. This structure is shown in Figure 33 and provides a combination of both

types of junctions with improved reverse breakdown,

lower noise, and control of the surface oxide-diode edge leakage.\(^{32}\)

Hybrid structures could be useful where a shaped intensity response is desired. The reverse-bias signal would be due to both parts of the hybrid while the forward response would only be due to the diffused

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junction area. The intensity response can also be shaped to some extent by extending the metal for some distance beyond the edge of the oxide hole as is shown in Figure 34. This provides an additional capacitance which can be used to modify the diode decay time without altering the material resistivity.

![Diagram of a Barrier Junction-Capacitor Array for Increased Storage Capacitance](image)

**FIGURE 34. A BARRIER JUNCTION-CAPACITOR ARRAY FOR INCREASED STORAGE CAPACITANCE**

In all cases, the signal producing charge distribution is a result of the carriers in the depletion region either being created within it or diffusing to it from the source side of the target. For X-rays where the carriers are produced more or less uniformly throughout the material, both processes occur so that the sensitive thickness of the target is equal to the depletion width plus the diffusion length. Surface recombination with deep penetrating
radiation is of secondary concern as long as the targets are not too thin. Thin targets for optical radiation are quite important and have been treated in some detail in the literature.\(^{(33)(34)}\)

One interesting application involves the control of the target sensitivity and spectral response\(^{(35)}\) by the control of surface recombination and diffusion with an applied electric field to the forward surface of the target. This technique could also be applied to low energy X-radiation.

Mention should be made of image defects where leaky diodes appear in the read-out as bright spots while oxide covered diodes appear as dark spots.\(^{(36)}\) Some indication of the defect density obtained with commercial silicon and the diffusion process used in this work can be estimated from Plate I which shows a typical vidicon dark image with the shorted diodes clearly visible. The linear arrangement of some of these defects would indicate that they are

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PIE E I. TYPICAL VIDICON DARK IMAGE WHERE
WHITE AREAS REPRESENT SHORTED
DIODES
due to dislocations of atomic planes in the target material. Little difficulty was experienced in making large area Schottky diodes which appeared to be insensitive to material defects and thus would seem a good candidate for low defect targets. Even with modern integrated circuit techniques, perfect targets still have relatively low yields. (37)

While reference has been made to vidicon type structures in this work, the same target structure could be used with a return-beam electron tube as in the image-orthicon where increased gain is obtained from electron multiplication of the returned beam. The operation of the target structure in producing the charge variations would be the same.

CHAPTER III
OTHER RADIATION

Beta Radiation

No discussion of the silicon diode mosaic array vidicon tube would be complete without indication of the possibility of wide application for imaging with other than X, γ or infrared radiation. As indicated in Chapter 2, the basic mechanism for the production of electron-hole pairs in the silicon target by X or γ radiation is fundamentally a two step process. An incident photon interacts with the target material through one of three dominant mechanisms to produce an electron with a certain fraction of the energy of the incident particle in the form of kinetic energy. This electron then travels through the target material losing its kinetic energy through the ionization of electron-hole pairs along its path until it is stopped or leaves the material.

By eliminating the first step in the two step process, energetic electrons or "Beta" rays can interact directly with the mosaic array target. Further, the elimination of the photon-to-electron interaction cross section greatly increases the sensitivity of the device to a given particle flux. In the X-ray case, not every photon produces an electron and even those which were produced would not, in general, possess kinetic energy equal to the energy of the incident photon.
In the detection of beta radiation, the mosaic array vidicon represents a highly sensitive, high resolution replacement for the traditional phosphorescent screen. The vidicon allows all the advantages of a television system, such as remote observation as well as those features unique to the silicon diode target, such as electronic zooming. Gordon and Crowell of Bell Telephone Laboratories have also recognized this sensitivity and have reported on an image-storage scan-converter tube\textsuperscript{1} constructed on this principle.

The storage property of the silicon diode target can also be used to increase sensitivity where the frame rate can be reduced. If the vidicon electron beam is blanked between successive read-outs, the integration time is limited only by the dark decay time of the target. Other than decay time, the basic limitations of this device in any scan mode are the relatively small available scan area and the necessity of the incident radiation penetrating a layer of the target material to reach the sensitive region. For electrons, the device is limited to incident kinetic energies greater than several KeV.

Because of the need of penetration, the basic sensitivity adjustment is the target thickness, and as was pointed out in Chapter II, proportionately more ionization is created at the end of an electron path than at the beginning. For maximum sensitivity it is

desirable to match the target thickness to the electronic range at the given incident energy. Normally, the minimum allowable target thickness limits the low energy beta sensitivity of the device particularly if the target must also provide a vacuum seal. 20 KeV electrons have a range in silicon of 10 microns, but it is possible to extend the depletion region toward the target surface by control of the material doping level or target voltage as was indicated in Chapter II. Thus, the vidicon sensitivity could be made proportional to the target voltage as is the case of photoconductive tubes and used for automatic sensitivity control. The low energy cut off of the device would also be electrically controllable. Straggling effects and the carrier diffusion provide sensitivity when the dead layer is greater than the range. The storage tube mentioned above was able to operate with electron energies as low as 2 KeV although more optimum operation was observed around 10 KeV.

A preliminary test for electron sensitivity was performed at the beginning of this research using a Strontium 90 beta source producing electrons with an energy of about 500 KeV, but no sensitivity was observed. However, the target used was about 1 mm thick and it is seen that a combination of the thick target with the relatively weak source could have led to this negative result. A better procedure would have been to use a "mylar" or other thin material window to support the vacuum in the tube with a thin target mounted separately inside.
The sensitivity of the mosaic vidicon tube is not limited to electrons. Any charged particle is capable of producing ionization in the semiconductor material and Figure 35 shows the energy deposition in silicon for incident protons as a function of kinetic energy. If this figure is compared to Figure 19 of Chapter I, it is observed that at 1 MeV a proton deposits 100 times the ionization per unit length of an electron. Thus for the case where the particles pass completely through the target, the device will be 100 times more sensitive to 1 MeV protons than electrons. In general, the heavier particles will not pass through the target since a 1 MeV proton has a range in silicon of only 15 microns. For an alpha particle, a kinetic energy of 4 MeV is required to obtain the same range. Thus in imaging with heavy particles, it is seen that a dense "cloud" of
charge will be created on the surface of the vidicon target and these carriers will tend to be dissipated rapidly both through surface recombination and "excess recombination" or the direct recombination of holes and electrons due to the high charge density. However, some carriers will still diffuse toward the junction and an image can be obtained. This loss can be necessary since as shown in Chapter I, a single 3.6 MeV proton will produce about one million electron-hole-pairs which can unbias the diode it strikes. For imaging purposes, no gray levels will be observed; only reverse biased or unbiased (except for lateral electron diffusion) diodes produce black or white. The "dead" target material thus acts as a moderator reducing the carrier density to a level usable by the device although lateral diffusion reduces the resolution of the image.

One application related to charged particle imaging which involves not so much the radiation sensitivity of the device but rather the discrete nature of the picture elements is particularly intriguing because of the increased use of on-line computers in experiments performed with linear accelerators. If the vidicon electron beam were swept with a staircase rather than a ramp voltage and arranged such that each step of the vertical and horizontal could be used to index a particular diode of the array, digital spatial information as well as the radiation intensity at that location could be produced for digital storage or direct calculation. Such an arrangement would be useful in X-ray crystallography where a direct calculation of structure could be obtained from the spatial data.
Photocathode Intensifier

A variation of beta sensitivity which takes advantage of the large number of electron-hole pairs created by each incident energetic electron is shown in Figure 36. Electrons emitted by the photocathode are accelerated by the high voltage potential, HV, and strike the mosaic target producing a large number of carriers such that a quantum gain is realized. The operation of the target and the remainder of the vidicon tube is as described for beta radiation above, thus both the target voltage or the acceleration potential could be used to control the sensitivity. Through the use of a photocathode, the response of this arrangement extends into the ultraviolet, but all the limitations of photocathodes apply.

FIGURE 36. ARRANGEMENT FOR CHARGE MULTIPLICATION USING A PHOTOCATHODE
Finally, in regard to particle imaging, mention should be made of neutron sensitivity, since neutron imaging finds application in nondestructive testing. If organic materials such as explosives enclosed in a metal container, X-rays are useless because at energies high enough to penetrate the container, the organic material does not appear due to a much lower mass absorption coefficient. Neutrons, however, have a high capture cross section in most hydro-carbons and thus can "see" the powder in a metal shell.

Since the silicon diode array is not sensitive to neutrons except through radiation damage, a secondary mechanism is necessary. As in the X-ray case, the interaction is a two step process. In the neutron case, the first interaction in which the neutron produces an energetic charged particle does not occur in the silicon target material but rather in a conversion layer in front of the target. Useful converter materials would be LiF or B\textsubscript{2}O\textsubscript{3} as discussed by Love.\(^2\) For a converter layer of thickness \(x\), the number of neutrons reacting per unit area are given by

\[
N = I_0 \left( 1 - e^{-\sigma x} \right)
\]

where \(I_0\) is the incident neutron flux and \(\sigma\) is the reaction linear absorption coefficient and is given by

\[ \sigma = \frac{\rho \sigma_a N A}{M} \quad (3.2) \]

where \( \rho \) is the converter density, \( \sigma_a \) is the reaction cross section, \( A \) is the abundance of the reactive isotope, \( N \) is Avogadro's number and \( M \) is the molecular weight of the converter material.

\(^6\text{Li}\), for example, has a thermal neutron cross section of 950 barns and produces an alpha particle and a triton in opposite directions sharing a reaction energy of 4.78 MeV yielding a macroscopic linear absorption coefficient of \( 57.4 \text{ cm}^{-1} \) for isotropically enriched material. For a conversion layer \( 40 \times 10^{-4} \text{ cm} \) in thickness, it is found that

\[ N = I \cdot (2 \cdot 10^{-6}) \quad (3.3) \]

or such a layer would react with about 20 percent of the neutrons striking it. Although the relatively heavy particles produced in the lithium reaction have a short range in the silicon target material, their large energy can produce enough ionization for imaging by the diffusion of carriers to the depletion region.

Heat

Possible application of the silicon mosaic array vidicon to heat imaging will be noted since, currently, rather slow optical-mechanical scanning mechanisms or temperature to color conversion methods such as the Evaporograph or liquid crystals are in use. There would appear to be a need for a device capable of operating at standard television frame rates. The temperature dependence of
the diode reverse bias decay time could be the basis of a heat imaging array vidicon tube. Next to sensitivity, the basic problem in the device would be lateral heat conduction in the target. The target material being a semiconductor helps the situation, but obviously an insulator would be more ideal.

Another method of obtaining heat sensitivity which takes advantage of the silicon array insensitivity to ultraviolet radiation, would be to employ a converter layer of heat sensitive phosphor. This material when irradiated with ultraviolet light glows with a characteristic color the strength of which is proportional to its temperature. A thin coating dusted on a transparent insulating layer applied to the front surface of the mosaic target could provide heat imaging when irradiated with ultraviolet light. Because of the silicon array is easily made insensitive to short wavelength radiation, the target would not be swamped by the UV source as might occur with a photocathode type of image tube.
CHAPTER IV

EXPERIMENTAL RESULTS

Single Diode Measurements

The theoretical analysis of the foregoing chapters indicated the possibility of the generation of electron-hole pairs in a semiconductor material by X or \( \gamma \) radiation as well as the possibility of imaging when used in conjunction with a standard vidicon structure. The experimental verification of these possibilities is necessary not only as support for the theoretical analysis, but also to obtain certain system parameters which would be difficult or impossible to obtain from the theory because of the approximations or simplifications involved. Empirical factors can then be used as lumped factors to describe phenomena such as silicon--silicon oxide surface effects or as limits to indicate the usable region of the simplified theory.

At the initiation of this research, there was no information in the literature relating to the X or \( \gamma \) ray sensitivity of mosaic diode arrays and thus, this application of the device was thought to be quite novel. Subsequent publications, however, have
shown that research in this area was underway,\(^{(1)}(2)\) although along somewhat less academic lines. Thus, it has been the purpose of this research experimentally to demonstrate the possibilities of the device in radiation imaging rather than to produce commercial quality pictures or develop methods for producing tubes at competitive prices.

While it would appear that the most straightforward method of demonstrating the sensitivity of the silicon mosaic diode array to penetrating radiation would be to construct large area single p-n junctions. It was found that this approach was not valid in all cases. For example, all attempts to produce a 1/2-inch diameter diffused junction failed. All were observed to be shorted. Apparently, an area of this size has nearly 100 percent probability of including a short causing defect of some kind. Various smaller area diffusions were produced with a good compromise being found in a .038" x .038" junction. Diodes of this size had a comparatively large area for sensitivity measurements yet also produced many good diodes. The dark reverse current obtained for two typical diodes is shown in Figure 37 as a function of the reverse bias voltage. The second diode is observed to have much greater leakage than the first, where leakage is indicated by a unit slope meaning that the current is proportional to the voltage and the junction has a resistive characteristic.

---


FIGURE 37. OBSERVED REVERSE BIAS CURRENT AS A FUNCTION OF DIODE BIAS VOLTAGE
Also shown is the generation current obtained under room illumination (standard fluorescent fixtures) and the voltage independent current generator characteristic is clearly evident.

Evidence that the dark current behavior cannot be directly extrapolated to smaller area diodes for all values of reverse bias is given by Figure 38 which shows the reverse current measured as a function of reverse bias voltage with small 500/inch junctions. The higher reverse current curve was obtained with diffused junctions. The other curve was obtained from barrier junctions constructed by depositing electroless gold through holes etched in a silicon oxide overcoat. While there was no diffusion in the second case, the oxidation procedure required nearly the same temperatures. Since the same 10-ohm-cm material was used in both cases, the diodes would be expected to be similar in characteristics. The odd behavior above 4 volts reverse bias observed in both cases gives evidence that on this scale, another mechanism is taking place. The odd effect is most likely due to surface phenomena as discussed in Chapter II.

With respect to the theoretical discussion of decay time, the slope of the dark current at low bias voltage is of interest. Since the dark current generation was assumed to vary with depletion width, a slope between 2 and 3 would be expected. It is observed that although there is a variation with reverse bias in the diffused diode, it is much less than expected and the barrier diode shows almost no variation at all. Thus, in the smaller size diodes, it is seen that certain adjustments might be necessary, such as the exponent by which the dark current changes with bias voltage, to provide an accurate
FIGURE 38. REVERSE DARK CURRENT AS A FUNCTION OF BIAS VOLTAGE FOR ARRAY DIODES
description of the device operation. These adjustments would be a
function of the junction size.

The primary purpose of the single diode measurements was
to determine the sensitivity of the mosaic arrays to X-rays. Since
the region of greatest interest was for X-rays of high energy with
good penetrating ability, it was convenient to use a substitute X-ray
source for the preliminary testing, particularly in view of the pos­
sible radiation hazard involved. An infrared lamp was used as a
substitute calibrated source. The deep penetration of IR wave­
lengths corresponding to energies near the band gap provide a
good simulation of X-ray penetration, particularly for X-rays with
energies such that the electronic range can be neglected.

The total energy produced by the infrared source was
calibrated for three conditions: first, a clear aperture; second, a
Kodak 72 infrared filter; and third, with the camera lens placed
behind the filter with the image such that the illumination was spread
evenly over an area about equal to that of a standard vidicon tube
target. The energy density as a function of the IR source intensity
control setting is shown in Figure 39. This set of curves provided
information by which various diodes and arrangements could be com­
pared. Since the open circuit diode voltage under illumination is a
measure of the generation rate and is relatively independent of the
junction area, this voltage was plotted for various diodes and the
results obtained appeared in most cases as shown in Figure 40. This
curve also shows that the open circuit voltage is too small at low
Lamp to Thermopile Distance:
2.56 meters

FIGURE 39. OBSERVED LAMP RADIATION AS A FUNCTION OF CONTROL SETTING
FIGURE 40. OPEN CIRCUIT VOLTAGE AS A FUNCTION OF LAMP INTENSITY

FIGURE 41. REVERSE CURRENT FOR LARGE AND SMALL DIODES AS FUNCTION OF LAMP INTENSITY
intensities to produce a good signal were the variation in the target current due to the diode voltage alone. The current which flows in an illuminated junction under reverse bias is also a measure of hole-electron generation and this is shown in Figure 41 for both large and small diodes. The characteristic is nearly linear with intensity provided the photo-generation current is large compared to the dark current.

It is the generation current which gives rise to the reverse bias decay in the vidicon array. Although it was not possible to observe the decay time on the small 500/inch diodes because of stray capacitance effects, variations in decay time with illumination level were observed using the larger .038 x .038 inch diodes. Figure 42 shows the arrangement for the decay measurement.

![Figure 42. Test Setup for Voltage Decay Measurement](image)
The diode shown in the circuit was a high speed-low capacitance computer switching diode and was used to isolate the pulse generator from the junction under test during the voltage decay. Figure 43 shows the results obtained for the test junction disconnected in the dark and for the three levels of illumination as listed in the figure. The disconnected junction plot is of interest not only because it gives the RC time constant of the apparatus, but also because it shows the deviation of the diode decay curve from a true exponential response as occurs with photoconductive targets. The disconnected junction response is faster than the dark response because of the lower system capacitance without the junction, but the dark decay-time is not the true diode decay due to the short scope impedance. It also may be seen from this figure that the illuminated junction does not decay to zero but rather to the open circuit junction voltage. This junction voltage provides a slight extension of the available decay time. Further, it is noted that at intensities as high as a milliwatt per square centimeter, any target array would be expected to be in a forward biased condition in a standard television frame period.
The lamp to junction distance was reduced to 50 cm and the curves of Figure 44 were obtained. These curves are quite similar to Figure 43 except that a "break" or "corner" begins to appear in the forward bias portion of the decay at high illumination levels. This is apparently due to the generated carriers being used to form the required minority carrier distribution required in forward bias so that the voltage then decays much slower.
An attempt was made to measure the charging current directly, but even with the relatively large diode area this was not possible at low illumination levels. The curve of Figure 45 was obtained at higher generation rates. It is seen to be similar to the results shown in Figure 41. Since equilibrium was reached within the $10^{-3}$ sec charging period for the illumination levels in Figure 45, this curve also represents the charge $\Delta Q$ required to reverse bias the junction at a given illumination level. In a vidicon system, this $\Delta Q$ would only occur at high generation rates, but it would give an indication of the expected signal at high illumination levels. An attempt was also made to measure the current produced by direct X-ray irradiation. It was found necessary to use the technique illustrated in Figure 46 because of the low carrier generation with the available X-ray flux. This technique did not prove to be accurate but did yield the data of Table 2.
FIGURE 45. DIODE CHARGING CURRENT OBSERVED WITH TEST SET-UP OF FIGURE 42, AS A FUNCTION OF INCIDENT ILLUMINATION
FIGURE 46. X-RAY SENSITIVITY MEASUREMENT APPARATUS

<table>
<thead>
<tr>
<th>X-ray Source</th>
<th>KeV</th>
<th>MA</th>
<th>Meter</th>
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<td></td>
<td>70</td>
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<td>50</td>
</tr>
<tr>
<td></td>
<td>60</td>
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<td>45</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>10</td>
<td>30</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>IR Calibration</th>
<th>Meter</th>
</tr>
</thead>
<tbody>
<tr>
<td>55 uw/an²</td>
<td>50</td>
</tr>
</tbody>
</table>

TABLE 2. OBSERVED X-RAY SENSITIVITY
Because more signal was required to directly measure the X-ray sensitivity and diffused junctions with larger areas could not be made, large area barrier junctions were constructed for this purpose. A 1/2-inch diameter circle of gold was evaporated onto a wafer of the 10 ohm-cm silicon material and a barrier junction was formed. The dark and room light generation characteristics are shown in Figure 47. It should be mentioned that the gold was evaporated through an aperture placed above the etched silicon surface rather than through a hole etched in the silicon oxide layer as was done previously. The infrared photo-generation current as a function of illumination is shown in Figure 48 and the reverse current as a function of the X-ray anode voltage is shown in Figure 49. The X-ray anode current was 8 ma. for all voltages and the test junction was located about 10 inches from the X-ray tube anode. The difference between the radiation incident on the front of the junction and on the rear is apparently due to absorption of the lower energy radiation by the silicon. This was demonstrated by placing the junction beneath a .091" thick aluminum plate, under which conditions the front and back irradiation gave very nearly the same reverse generation current. The reverse current as a function of reverse bias voltage is shown in Figure 50 for no radiation and for 40 and 90 KeV anode potential at 8 ma.anode current. The results are similar in character to that obtained for infrared radiation.

For completeness, it should be mentioned that At, the alloy junction, type of diode construction was attempted but was not
FIGURE 47. REVERSE CURRENT FOR DARK AND ROOM LIGHTS AS A FUNCTION OF BIAS VOLTAGE.

FIGURE 48. REVERSE CURRENT AS A FUNCTION OF ILLUMINATION FOR BARRIER DIODE.
FIGURE 49. REVERSE CURRENT OBSERVED AS A FUNCTION OF X-RAY MACHINE ANODE VOLTAGE

FIGURE 50. X-RAY PRODUCED REVERSE CURRENT OBSERVED AS A FUNCTION OF DIODE BIAS POTENTIAL
PLATE II. THE TELEVISION SYSTEM
Aluminum dots were evaporated on the silicon wafer which was then raised to the silicon-aluminum eutectic temperature in an inert atmosphere. However, with the equipment available, it was not possible to prevent oxidation or lifting of the aluminum before alloying would take place.

Vidicon Results

While the foregoing single diode data helps to demonstrate the X-ray sensitivity of silicon p-n and barrier junctions and justify some of the approximations used in the development of the interaction theory, the basic goal of this experimental research was the demonstration of a new X-ray sensitive imaging device, the silicon diode mosaic array vidicon tube.

The television system shown in Plate II was used for most of this work and was of minimum quality, consisting of a home type closed circuit camera (Sylvania Model 101) and a Zenith table model receiver. The resolution was about 400 television lines and because of severe synchronization instabilities, separate horizontal and vertical synchronizing cables were run from the camera sweep circuits to the receiver. Difficulties were still present consisting primarily of poor vidicon retrace blanking resulting in uneven picture shading.

Silicon array targets were evaluated with demountable tubes and for this purpose the camera deflection yoke assembly was modified by the addition of an "O" ring vacuum seal connection for evacuation through a stem in the tube base. Initially, an oil diffu-
sion pump was used to obtain a vacuum but this resulted in a build-up of an organic insulating layer on the target. A Varian Vac-Ion pump was then added as is seen in Figure 15. Except for the addition of an external target voltage supply and an adjustable vidicon heater supply, no other modifications were made.

The vidicon tubes were constructed with Superior Electronics Se-200 V vidicon guns which were supplied mounted on glass evacuation stems. Copper or nickel screen mesh, measuring 500 or 750 lines per inch was mounted in stainless steel rings and spot welded to the target end of the gun. Pyrex envelopes were attached to the gun stem with low vapor pressure epoxy after it had been sand blasted to improve bonding, and because of continuous pumping no bake-out was required. A typical tube with the various target components is shown in Plate III.

Diode arrays measuring 150 x 150 and 500 x 500 diodes/in² were constructed using standard integrated circuit technology on 5 to 17 ohm-cm, 20 mil thick slices of n-type silicon. After lapping to a high polish on one side, the wafers were oxidized in water vapor for one-half hour at 1100 degrees C. An oxide layer about 5000 Å thick resulted. Photoresist was placed on the polished side using a 6:4 mixture of K.P.R. and thinner with each wafer positioned on a spinner rotating at 3450 rpm. After exposure through a mask, the film of photoresist on the wafer was developed and rinsed methanol followed by ether. The developed wafers were then baked in a nitrogen atmosphere for 20 minutes at 180 degrees C and when cool, the
PLATE III. A VIDICON TUBE
exposed oxide was removed using a buffered HF solution consisting of 20 gm NH₄F, 30 ml. of distilled water, and 5 ml. of HF. The etch rate for this solution is about 1000 Å per minute. Removal of the photoresist was achieved by boiling and swabbing using "Q"-tips in trichloroethylene, rinsing in alcohol and finally in hot H₂SO₄ to remove all traces of organic materials prior to diffusion.

Junctions were formed at a depth of 3 x 10⁻⁴ cm by diffusion in a closed box at 1250 degrees C containing a small amount of H₃BO₃. After diffusion, the wafers were boiled in distilled water, HNO₃ and etched in buffered HF for 1/2-minute to remove the oxide formed during the diffusion process. The diode side was then masked to prevent scratching and the back surface was lapped to the desired thickness and etched in CP₄ to remove the lapping damage. The target thickness in this investigation ranged from 5 to 18 mils. In some cases, after removal of the mask and cleaning, the etched side was covered with thermal tape and the diodes plated with electroless gold. The gold seemed more a factor in the tube life, however, rather than in the quality of image attained in a new tube. An n-type contact was formed on the wafer by the diffusion of a lithium ring around the edge of the wafers and the arrays were mounted in a brass or stainless steel ring with low vapor pressure epoxy, using a small amount of Gallium-Indium eutectic to make electrical connection. A section of the complete target assembly is shown in Figure 51 and the photoresist arrangement used in producing the arrays is shown in Plate IV. This construction method was maintained throughout the research and seemed to be quite usable.
FIGURE 51. THE TARGET ASSEMBLY
PLATE IV. PHOTO RESIST DRY BOX
The first efforts with the vidicon system were directed toward obtaining images with an infrared source and initially relatively low resolution targets having a diode spacing of about 150/inch were employed. Plate V shows a typical picture obtained with these arrays. Many target defects were present, the white spots being shorted diodes, and smearing is evident.

It was discovered that the spacing between the final grid and the target had a definite effect on the overall sensitivity of the device. It was observed, for example, that a decrease in this spacing from .25 inch to .02 inch resulted in about a 200 fold increase in sensitivity, but the picture became smeared with the trailing of white lines. The test arrangement of Figure 52 was constructed to investigate the spacing of effect and while at first it was believed that the increased sensitivity was due to a change in the electric field strength as seen by the target, it was later observed that the variation of $V_4$ in the positive sense from 0 to 64 volts had little effect on the vidicon sensitivity. If $V_4$ were negative, defocusing was observed. Plate VI represents an infrared picture obtained in the most sensitive condition and good contrast was possible with illumination levels as low as 20 uwatts/cm$^2$, but smearing was very bad. Thus, some compromise spacing would appear desirable to produce maximum sensitivity with acceptable picture smear. The amount of smearing expected can be calculated from the circuit of Figure 53 where $C_0$ is the effective grid-target capacitance and where the input impedance of the video amplifier is 100 k
PLATE V. INFRARED TELEVISION DISPLAY WITH TYPICAL 150/INCH MOSAIC ARRAY VIDICON
PLATE VI. PICTURE OBTAINED WITH VIDICON TUBE
INCORPORATING ADDITIONAL TARGET
GRID
ohms. If the electron beam resistance can be neglected, the time constant for a grid-target spacing of .02" is given by

$$\gamma = RC = 10^5 \times 3 \times 10^{-9} = 3.6 \times 10^{-5} \text{sec} \quad (5.1)$$

which is a smear factor of about 12 TV lines and is in good agreement with the observed picture quality.

FIGURE 53. TARGET-MESH EQUIVALENT CIRCUIT
Since the increasing sensitivity with decreasing spacing was not due to the field strength, it was concluded that the effect was most likely due to the capacitance between the individual diodes in the array and the grid increasing the dark decay time. To test this hypothesis, a special target was constructed as shown in Plate VII where an evaporated aluminum dot was deposited over the oxide and part of the diode surface so as to place a fixed MOS capacitor in parallel with each diode in the array. This appeared to have little effect on the vidicon sensitivity but it is still not certain if good contact was made to each diode by the aluminum or if a barrier or series resistance of some kind was present.

After usable infrared imaging was obtained, the X-ray sensitivity of the device was examined. The low resolution 150 x 150 /inch array was used to produce the X-ray shadowgraph of a screw seen in Plate VIII. It was found that with the X-ray machine used, pictures could be obtained for anode voltages from 45 to 70 KeV at an anode current of 10 ma. This particular machine was calibrated and Table 2 shows the radiation measured to produce an image at the vidicon target.

<table>
<thead>
<tr>
<th>Absorber</th>
<th>KeV</th>
<th>Ma.</th>
<th>R/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horn</td>
<td>70</td>
<td>10</td>
<td>1.24</td>
</tr>
<tr>
<td>Mylar</td>
<td>70</td>
<td>10</td>
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<tr>
<td>Mylar</td>
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<td>.84</td>
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<tr>
<td>Mylar</td>
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<td>9.2</td>
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</tr>
<tr>
<td>Mylar</td>
<td>45</td>
<td>8.5</td>
<td>.625</td>
</tr>
</tbody>
</table>

TABLE 3. X-RAY MACHINE CALIBRATION DATA
PLATE VII. MICRO-PHOTOGRAPH OF ALUMINUM DOTS EVAPORATED ONTO THE DIODE ARRAY
PLATE VIII. X-RAY TELEVISION SHADOWGRAPH OF SCREW
PLATE IX. HIGH RESOLUTION INFRARED IMAGE
PLATE X. INFRARED SHADOWGRAPH OF SMALL GLASS DIODE
PLATE XI. X-RAY SHADOWGRAPH OF SMALL GLASS DIODE
The best results in demonstrating X-ray penetration of objects were obtained with the higher resolution 500 x 500/inch arrays. These arrays had good resolution and a relatively low/defect level as evidenced by the infrared image in Plate IX although the camera system and construction techniques continued to provide shading problems.

Plate X shows the infrared outline of a small glass encapsulated diode placed on the vidicon tube face, while Plate XI shows the same set up irradiated by the X-ray machine with 70 KeV at 10 mA anode conditions. Lower anode potentials produce an outline but no internal details of the diode. Thus using the horn absorber data of Table 2 since it is less sensitive to lower energy radiation, it is seen that good images can be obtained with a flux level of

A comparison of Plate X and XI led to the suggestion that the sensitivity of the device to various radiation could be put to use by an arrangement where a color was assigned to each image. For example, the infrared image could activate the red gun in a color set, low energy X-rays the green and high energy X-rays the blue, producing a color image in which various phases of penetration in the object are represented. Such a device would appear to have application in non-destructive testing or quality control. This refinement, however, has not yet been attempted.
CHAPTER V

CONCLUSIONS

By analogy with silicon diode radiation detectors, it was initially proposed that the silicon diode mosaic array vidicon tube should also possess radiation sensitivity. It was the purpose of this research to demonstrate this capability, particularly with respect to X-radiation of sufficient penetrability to be of use in non-destructive testing. The X-ray sensitivity of this device has been demonstrated by Chester and Koch\(^{(1)}\) for energies below 10 KeV, but it is believed that the research reported here represents the first demonstration of X-ray sensitivity for energies as high as the 70-90 KeV range.

The theoretical treatment of the X-ray interaction in the target material represents a significant contribution to the field, not so much for novelty, but rather in the sense that the well known physics of photon-material interactions has been applied to this new device such that its operation becomes defined in terms of accepted physical mechanisms. Thus, in any given application it is possible from an engineering point of view to optimize the structure in any desired parameter. Given a certain flux to be imaged, by the

\(^{(1)}\) Chester and Koch, Op. Cit.
approximal theory given, engineering limits can be set on the system performance before device construction. This greatly reduces the amount of required empirical adjustment.

While a somewhat more detailed treatment of the theory of junction decay was available in the literature, this was expanded, not only to include doping gradient, but also to include several carrier generation dependencies. It was shown that hole-electron pair generation current may or may not be a function of depletion width for penetrating radiation, depending upon the specific target and radiation. Further, the junction theory was extended to include the minority carrier charge distribution variation as well as the majority carrier distribution, although in a rather inexact fashion as the depletion approximation was used in a condition of small forward bias. Nevertheless, a non-storage, high illuminating flux imaging mode was predicted and also experimentally observed. Through proper combination of the reverse and forward bias signal producing mechanisms, a device with an extremely wide dynamic range can be produced. No discussion of this possibility or of any video signal producing mechanism other than reverse bias decay has been found in the literature and thus, this research is believed to represent the first theoretical discussion and experimental demonstration of high intensity mosaic imaging.

Although this research is intended to be primarily a discussion of the X-ray sensitivity of the device, throughout this
discussion the versatility and wide applicability to other imaging situations is stressed and Chapter IV can be considered as a recommendation for future work. Other recommendations would include the refinement of the calculations where possible or practical and also the extension of the mosaic diode array concept to other semiconductor materials with properties more suitable to specific applications. Materials with high atomic number might be used for greater sensitivity to X-rays of an energy such that the photoelectric mechanism is dominant.

It is concluded from this work that the mosaic diode array concept is inherently advantageous, particularly so for X-ray imaging. It is believed that this work also represents an advance in image tube technology not only because of the possibility of a trouble free, mass produced, inexpensive device, if manufactured with current integrated circuit techniques, but also because it can represent an improvement in performance for X-radiation or for any radiation to which the target is sensitive.
APPENDIX A

Silicon Diode Junction Depth Nomograph
(After Dearnaley Op. Cit. (10))

Voltage applied \( V \) volts

| Voltage applied \( V \) volts | Barrier depth \( E \) \( (\text{MeV}) \) | Capacitance \( C/\text{cm}^2 \) \( \text{pF} \) | Impurity
<table>
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<tr>
<td></td>
<td></td>
<td></td>
<td>concentration ( n/\text{cm}^3 )</td>
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<tr>
<td></td>
<td>Range energy ( (\text{keV}) )</td>
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</tr>
<tr>
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\( \text{P} \)-type

\( \text{N} \)-type

Range energy \( (\text{keV}) \)

Proton \( (\text{Imn}) \)

Impurity concentration \( n/\text{cm}^3 \)

Resistivity \( \rho_n \)

Resistivity \( \rho_p \)
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