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ALPHA PARTICLE IMAGING WITH A SILICON DIODE
ARRAY VIDICON TUBE.

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ALPHA PARTICLE IMAGING WITH A SILICON DIODE 
ARRAY VIDICON TUBE

Dissertation

Presented in Partial Fulfillment of the Requirements 
for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

by


* * * * * * * * * *

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PREFACE

Over the past decade the development of semiconductor junction radiation counting devices has revolutionized experimental work with nuclear or machine produced radiation of all types. During this same period a rapid move from discrete components in electronic circuitry to integrated circuits was taking place which perhaps has created a greater impact upon electronic systems than did the transistor itself. The work described in this dissertation combines much of the understanding and technology of both of these advancements in the development of a silicon p-n junction array target vidicon image tube having alpha particle sensitivity.

Given in the Introduction is a survey of the earliest developments and applications of this type of image tube. Since the referenced literature can be examined for detailed description of the image tube only a brief discussion of the basic mechanisms of target response and signal generation is given in this writing and is covered in Chapter I.

The experimental work is presented in Chapter II which includes target construction and tube assembly, the experimental arrangement, and the procedure and image results obtained. Since there was no theoretical description to date, of minority carrier diffusion from an initial high concentration line source, as is caused along the
linear path of an ionizing alpha particle, an effort to describe this phenomena is given in Chapter III. Also given in this chapter is a theoretical description of an image tube for neutron radiography where the demonstrated alpha sensitive tube is provided with an energetic alpha emitting neutron converter layer placed in front of the image tube target. Some concluding remarks are made in Chapter IV along with recommendations which should prove beneficial in the construction of improved alpha sensitive image tubes and for demonstrating a neutron sensitive tube.

I would like to take this opportunity to thank my graduate advisor, Professor Donald D. Glower, for the guidance and advice which he provided during the period of this work and particularly for his encouragement throughout my graduate studies program. I am grateful to Professor William W. Anderson of the Electrical Engineering Department for his interest in this and the preceding work on these image tubes which resulted in many helpful discussions and comments. My thanks also to Professor Robert F. Redmond for his interest and suggestions leading to the mathematical prescription for the solution of minority carrier diffusion. I am further grateful to these three men for serving on my reading committee and final oral examination.

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I thank the Department of Electrical Engineering for the use of space and equipment required in performing the experimental work of this dissertation.

I thank Mr. Pagean for cutting the single crystal silicon and doing the photography work.

For her help in preparing and typing this dissertation, I thank Mrs. J. Balch.

For having a seemingly endless capacity for sacrifice and enduring patience I thank most of all my wife and children.

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INTRODUCTION

A combination of theoretical and experimental work with solid state particle and gamma ray radiation detectors, solar energy converters, and the primary energy conversion components for solid state infrared image converters led to proposing a semiconductor p-n junction mosaic target for incorporation into a new and very broad range radiation image tube. In the original conception, four distinctively different imaging ranges were recognized, distinguished primarily by their mechanisms of radiation interaction with the image tube target. These ranges were: low energy electromagnetic radiation, high energy electromagnetic radiation, charged particles, and neutrons. The work presented here is concerned with the latter two areas.

Imaging with heavy charged particles, per se, is limited to a small number of important but rather intricate experimental or analytical applications which depend on individual particle position sensitivity. Examples are: atomic scattering of incident particles from a collimated beam (Rutherford scattering) and transmission diffraction through a thin layer of crystalline material. The principle method of image recording to date has been with scintillation screens or photographic film.
Although electron transmission microscopy has been widely used as an analytical tool, imaging with heavy charged particles has been a neglected area. There has been two primary reasons for this. First, a suitable camera has not been constructed which permits detection of short ranged particles, particularly alpha particles, while maintaining spatial as well as flux or energy resolution (with the possible exception of photographic films) and second, the need for such a system has been minimal because of the limited penetration depth of the particles in samples to be studied. Advances in technology however, have produced an increasing need for greater precision in analyzing the internal structure of a broad range of solid state thin films and biological specimens, in addition to new scattering experiments in physics. The intrinsically better charged particle position sensitivity of the new image tube is particularly suited to many of these measurements.

Another possible application of a heavy particle image tube is its utilization as a pin-hole camera for recording source distributions. The camera would operate, in principle, like the common pin-hole optical system.

The work described in this dissertation was directly concerned with the construction of the silicon p-n junction mosaic array target vidicon tube and its evaluation for alpha particle imaging. Toward this end, 0.001 inch thick arrays were fabricated having a diode density of 500 x 500 per square inch. Imaging experiments were performed using alpha particle emissions from a one micro Curie Am²⁴¹
source. Theoretical analysis of the experimental arrangement is also given.

Since thermal neutrons incident on a Li\textsuperscript{6} neutron converter layer will produce energetic alpha particles, a brief investigation of the possibility of neutron imaging was made. It was found however, that the techniques employed to obtain 0.001 inch thick targets were insufficient for fabricating thinner and more defect free targets required for the shorter ranged alpha particles from the converter. A theoretical discussion however, is made which presents the feasibility of this arrangement for neutron imaging.
CHAPTER I

THE P-N JUNCTION ARRAY TARGET VIDICON IMAGING TUBE

Image tubes employing a scanning electron beam for television display have ordinarily been constructed with targets having a uniform layer of photoconductive material which serves to regulate charge leakage through the layer proportional to the flux intensity of the radiation containing the image information. The type of photoconductive layer used in the tube depends on its intended application. In the visible range, \( \text{Sb}_2\text{S}_3 \) or PbO in a graded p-n junction form have been extensively used. X-ray sensitive tubes, until recently, have been constructed using PbO, CdS and selenium layers.\(^{(3)}\) For neutrons, the display is generally obtained using one of a variety of developed cameras\(^{(4)}\) along with converters, phosphors, optics and image intensifiers, each of which contribute to reduction in resolution.

1.1 Basic Target Structure

A new type of target, shown in Figure 1, suitable for use in scanning beam image tubes of the vidicon or orthicon type has been developed which consists of isolated p-n junctions as suggested for optical imaging by Heijne\(^{(5)}\), first demonstrated for the optical region for silicon arrays by Crowell, et.al.,\(^{(6)}\) and generally discussed for imaging with IR, X-rays, gamma-rays, charged particles, and neutrons.
Figure 1. Vidicon target assembly.
by Harpster, et al. (7) and Jacoby (8). Pertinent characteristics of the target are its high sensitivity, fast response with no image lag, ability to operate over a wide intensity range, and lack of degradation due to electron beam interaction at high image intensity. Damage, however, would occur for high energy radiation as is characteristic of any semiconductor device. However, for imaging, the flux requirements can be very small thus, allowing many hours of tube operation before any change in the highly damage sensitive minority carrier becomes noticeable.

1.2 Target Operation

Since the silicon mosaic vidicon tube is relatively new, a brief description of its operation for optical excitation will be given. This will then be followed by a preview of particle excitation.

The video signal can be obtained from the discrete junction elements in essentially two modes of operation. These are a reverse bias mode as discussed by Heijne (5) and Crowell et al. (6), and a photovoltaic mode as detailed by Jacoby (8). Briefly, in the reverse bias mode, each diode operates in a manner shown in Figure 2. The diode's capacitance is charged to essentially cathode potential with a charge $Q^+$ as the beam passes. A charge $\Delta Q^+$, which makes up the video signal, leaks away in a time $T$ as a result of electron-hole pairs generated in the depletion region $D$ or from minority carrier diffusion of
Figure 2. Schematic representation of single diode operation in the mosaic array.
charges generated thermally or by radiation in the base region B at a rate $\epsilon I A$ where $\epsilon$ is a radiation- and target-dependent efficiency factor, $I$ is the radiation flux and $A$ the effective diode area. (It is the minority carrier diffusion component of current which dominates in supplying signal charge and provides the basic difference between this system and the solid state nuclear radiation detector.) The time $T$ is the electron beam sweep time (1/30 sec. in commercial television systems). For the reverse bias mode of operation, the primary requirements to be met are: 

1. the dark current leakage (space charge generation and diffusion currents) must be less than the generation rate $\epsilon I A$,

2. the leakage, $\Delta Q$, is less than $Q$ otherwise saturation would occur, and

3. beam current must be sufficient to take the diodes back to the reference level near cathode potential. The requirements for (1) are easily met. The dynamic range or latitude is limited in this model by (2) and possibly by (3). Observation of output signal as a function of incident intensity indicates a very wide dynamic range of the tubes with little degradation in monitor quality to the point where the signals saturate the amplifier or produce over modulation. It is therefore, suggested that at least one other high level mechanism is possible which produces the video signal.

At high excitation levels or low beam currents the diodes cannot be reverse biased. Instead, the diodes develop a photovoltage proportional to the radiation-induced generation rate. The charge
associated with this voltage is removed when the beam sweeps past giving rise to the video signal. This signal would have a fast rise time and a decay similar to that discussed by Pell\(^9\) for injected minority carriers.

Presumably, a smooth transition from reverse bias mode to photovoltaic mode occurs for a given electron beam current as the incident radiation level is increased which explains the wide dynamic range of tube operation. Further, for a given beam current the reverse bias mode is useful for radiation flux integration as discussed in detail for p-n junction photodetectors by Weckler\(^{10}\). The time \(T\) between scans may be increased by delaying successive sweeps which provide a larger \(\Delta Q\) resulting in larger video signals. Without incident radiation, the deposited charge from the electron beam will leak away in a time of the order of seconds for high quality targets at room temperature. This leakage current is dependent on equilibrium minority carrier diffusion and space-charge generation current which decreases with decreasing temperature. Integration time for imaging would be very useful for low radiation flux levels. Chester and Koch\(^{11}\) have used this to build-up signals from low energy X-rays in a crystal orientation application.

Heavy charged particles such as protons and alpha particles can interact directly with the target to produce an image. Individual particles having energies greater than 0.1 MeV can deposit energy in
the diffusion collection region, $D$, of one diode, providing sufficient charge, if collected, for video recording as determined by IR sensitivity measurements $^{7,8}$ and will be discussed further in Chapter III. This effect becomes extremely important for low intensity fluxes where time integration techniques, such as, TV loop tape storage or photographic integration at the monitor of individual interactions, can be used to build picture contrast. A more detailed theoretical discussion of alpha particle interactions will be given in Chapter III.

Because of the low absorption cross-section in silicon for neutrons, a converter layer in front of the target becomes necessary. Useful converters would be $\text{B}_2\text{O}_3$ or $\text{LiF}$ as discussed by T. Love $^{12}$ for a neutron spectrometer. For this application the converter layer could be much thicker than is required for spectroscopy work. $\text{Li}^6$ has a thermal neutron $(n,\alpha)$ cross-section of 950 barns with energetic $\alpha$ and triton product particles emitted sharing a reaction energy of 4.78 Mev which then interact with the target to produce charged carriers. A detailed theoretical discussion of applications to neutron imaging will be presented in Chapter III.
CHAPTER II
EXPERIMENTAL WORK

Experimental work during the course of this project included the construction of vidicon tube targets suitable for alpha particle imaging and their evaluation. Techniques were developed to obtain targets of minimum thickness. This was required in order to have a sufficient number of alpha particle induced minority carriers collected by the diodes by diffusion to provide a video signal. It was considered desirable to have most if not all of the $\alpha$ particle track within a diffusion length of the junctions. Target evaluation was performed using an Am$^{241}$ alpha source.

Also, during the course of this work, an unsuccessful attempt was made to determine if one of these targets could be made neutron sensitive using natural lithium containing 7.4% Li$^6$ as a converter. Preliminary discussion of this effort is given in this Chapter. However, a more detailed argument of neutron imaging is given in Chapter III following a theoretical discussion of the experimental arrangement.

2.1 Target Construction

The method of target construction is similar to what was done previously for X-ray sensitive targets(7) and is given in more
detail in the dissertation by Jacoby\textsuperscript{(8)}. Only a brief summary of
this past work will be given here followed by a more detailed dis-
cussion of the method developed to obtain 25 micrometer thick tar-
gets. The stepwise procedure is as follows:

(1) Wafers of 10 ohm-cm n-type silicon are cut to .020"
thickness from a .75" to .875" diameter single
crystal rod.

(2) These are lapped using 800 grit silicon carbide
compound and mechanically polished on one side with
9 and 3 micrometer diameter Al\textsubscript{2}O\textsubscript{3} powder.

(3) The polished side is masked with Apeazon wax and the
opposite side chemically etched in modified CP\textsubscript{4} etch.

(4) After cleaning, the wavers are given a 5,000 Å thick
oxide layer using the steam oxidation method at a
temperature of 1150°C for 30 minutes.

(5) Using KPR photoresist, square holes are opened in the
oxide layer on the mechanically polished surface. The
holes are approximately 25 micrometers on a side and
located on 50 micrometer centers.

(6) Boron is diffused through the openings to a depth of
3 micrometers using the closed boat technique and
B\textsubscript{2}O\textsubscript{3} source at a temperature of 1100°C for 20 minutes.

(7) After lapping and etching the target on the undiffused
side to a thickness of 25 micrometers, it is mounted
in a stainless steel ring using Torr Seal epoxy. Contact between the mounting ring and the base region of the mosaic is made using GaIn eutectic.

(8) The target is mounted on a vidicon gun for testing and evaluation as previously shown schematically in Figure 1.

The above is an over simplification of the details involved in target construction. For greater clarity the details of steps (4) and (5) are given in Appendix A. This procedure is presently being used as a standard photoresist procedure, primarily because of excellent reproducibility. Step (7) is described in detail below.

In order to thin the wafers to 25 micrometers thickness, carefully controlled etching procedures were required and developed. An etching solution of 5:3:3 of HNO$_3$ : HF : CH$_3$COOH was mixed and allowed to stand for 1/2 hour to reach thermal equilibrium. Sixteen lapped wafers were etched for 2, 4, and 6 minutes resulting in measured etching rates of $1.05 \pm 0.05$, $1.04 \pm 0.05$, $1.00 \pm 0.02$ mils/sec, respectively, with the average result of $1.03 \pm 0.03$ mils/sec. Several methods were tried to obtain uniformly thin targets. Only the most successful of these efforts will be discussed here.

Diffused array wafers were alternately mounted in a circle three at a time on a lapping disc along with 3 circular microscope mounting plates measuring .005" thick which served as a silicon thickness indicator and also to help maintain planarity. The wafers were
then lapped to the predetermined .005" thickness using an automatic lapping machine. After removal, the slices were cleaned in trichloroethylene and methyl alcohol. The diode side was then masked with trichloroethylene diluted Apeson wax and mounted on a holding rod as shown in Figure 3. Relatively flat and uniform etching of the wafer was obtained by rotating the wafer around the axis of the holding rod while the wafer was immersed in a rapidly stirred etch as given above for the desired time. The resulting cross section is shown in the inset of Figure 3. Although an extremely uniform flat central region is obtained, the periphery is feathered because of a more rapid etching rate at the wafer edge. During etching, feathering occurs and the diameter of the wafer is reduced at a rate much greater than the rate of thickness reduction. In order to maintain a suitable target diameter, the etch must be stopped resulting in a minimum obtainable target thicknesses of .001" to .0015". The thin targets were then mounted as discussed earlier. Although larger diameter silicon could have been used initially, it was not obtainable during the course of this work.

Plate 1 shows a silicon mosaic target mounted in the stainless steel ring which also serves as the signal contact. The two small holes in the ring allow for evacuation of the source and sample chamber. At .001" thickness, the wafer becomes transparent to the longer wavelength red radiation from a visible light source.
Figure 3. Method of etching thin silicon wafers.
Plate 1. Junction array target in ring mount.
The filament of a tungsten lamp in a microscope illuminator can be seen through a target as shown in Plate 2.

2.2 Experimental Apparatus

The basic electronics used in this work consisted of a closed circuit TV camera, Olson Radio, Model TV-132, modified by re-mounting the filament and power supply transformer to allow for image tube evacuation connection at the rear as shown in Plate 3. Also shown, are an oil diffusion pumping station on the right which is used for initial tube and system evacuation and a Varian vac-ion pump located directly behind the camera. The vac-ion pump is used to obtain a relatively oil free vacuum of about $10^{-7}$ torr during operation of the tube. A GE home TV set was used for display. A special variable voltage filament supply was required since cathode heating from the camera filament supply of 6.3 volts is insufficient to provide the required beam current from the inactivated cathode.

2.3 Experimental Procedure and Results

The procedure and results to be described here will deal only with the pertinent features of the work; that is, obtaining a TV display resulting from signals generated by alpha particle interactions within the target. It should be mentioned however, that approximately 30 targets were constructed, mounted, and evaluated in the camera using IR and visible light. These targets had a
Plate 2. Light transmission through a thin silicon target.
Plate 3. Experimental apparatus for imaging.
variety of thicknesses and nonplanar geometry which provided associated information in developing the required technology for the construction of the final arrays.

Mounted targets showed alpha interaction flashes on the TV monitor from an Am\(^{241}\) source mounted in the evacuated envelope of the vidicon tube. The arrangement is better shown in Plate 4 and with greater clarity in Figure 4. The alpha source holder was a disc measuring approximately 3/4" diameter and 1/4" thick. This was surrounded on the edges by a wrapping of aluminum foil to keep it stationary in the tube extension. Because of the high sensitivity of the target to stray light, the end of the camera containing the target was completely wrapped in photographers black cloth.

For the arrangement to be useful as intended, the observed monitor flashes must be the result of individual alpha interactions rather than a combination of two or more particles interacting near the same diode in a time which is short compared to the interrogation period of 1/30 sec. The decay rate of the Am\(^{241}\) source was approximately 1 micro Curie and it was located about 2 cm from the target. The area of the target being scanned by the electron beam was 1 cm x 1.3 cm and this region contained 5 x 10^4 diodes. The probability of a two-alpha interaction with one of the array diodes under the above conditions is 2 x 10\(^{-7}\) as derived in detail in Appendix B. Therefore, on the average, it would take 5 x 10^6 picture frame scans or 46 hours to observe a 2 alpha interaction.
Plate 4. Image tube and Am^{241} source mounted in camera.
Figure 4. Schematic of alpha particle image tube and camera.
The flashes which appear on the monitor are at a much higher rate. On a 1/2" x 1/2" area of the monitor, the rate is approximately four per second. The total monitor format is approximately 188 in.\(^2\) giving 752 monitor flashes per second. This amounts to 25 monitor flashes per frame sweep which compares well with the estimated 32 interactions from the Am\(^{241}\) source given in Appendix B.

To demonstrate the radiographic aspects resulting from patterned interaction with a uniform alpha flux, a wing and leg of a fly were mounted directly on the target facing the Am\(^{241}\) source. Mounting was performed by dissolving Lucite plastic in trichloroethylene and placing a small drop on the target and then gently placing the object on the glue dot. On drying, very little residual plastic remained. However, it provided sufficient strength to hold the objects in place without noticeably effecting the tube vacuum or providing significant alpha particle absorption.

A photograph of the monitor taken in 1/25 sec. is shown in Plate 5 using the 1 micro Curie Am\(^{241}\) source located approximately 2 cm from the image and target plane. The dominating features observed in this picture are charge leakage defects caused during fabrication or inherent in the silicon used for target construction. Fortunately, however, this is not characteristics of industry's ability to fabricate defect free silicon mosaic targets as evidenced by Bell Telephone's Picturephone results\(^6\). In the monitor picture however, are the localized bright flashes which are the result of the 25-32 alpha
Plate 5. One frame sweep radiograph showing no image detail.
interactions per frame sweep discussed earlier. A time exposure of the TV monitor should however, provide a discernible image. After decreasing monitor brightness and stopping the photographic camera down from 5.6 to 11 and exposing the film for 6 sec., contrast becomes sufficient as shown in Plate 6, for observation of both the leg, in the upper left hand corner, and the wing, in the upper center portion of the picture. Thickness measurements of the fly wing using a micrometer showed that the leading edge of the wing (upper edge) was .001" thick and very nearly .005" thick near the wing tip. The trailing edge, lower right, tapered to an unmeasurable value. No measurements were made on the leg since its obvious thickness was great enough to completely stop the incident alpha particles. The thickness of the extremely thin webbing layer between the structural members of the wing does not appear to be great enough to absorb a measurable amount of alpha energy.

Magnification of the fly wing as shown in Plate 6 is 13.2 X as determined by direct measurement of the overall wing length and scan width of the target. The measured width of the leading edge rib in Plate 6, however, is 20 times greater than the microscopically measured width of 50 micrometers. This difference is directly related to the basic resolution of the target. Since the diodes are 25 micrometers across and separated by 25 micrometers, the basic resolution would be 50 micrometers for the case of no lateral charge
Plate 6. Multi-framesweep radiograph showing image detail.
diffusion or particle scattering. However, if an alpha particle causes discharge in four nearest neighbor diodes, the basic linear resolution would be approximately 75 micrometers or .003" i.e., the width of two diodes plus their separation distance. The 50 micrometer rib width would, if four nearest neighbor diodes were active, result in a rib width display of 75 x 13.2 = 0.99 mm in Plate 6. The minimum measured width of the leading edge wing rib in Plate 6 is 1 mm which is in good agreement with the above.

Examination of the narrower inner ribs in Plate 6 shows the same basic 1 mm width. However, they look smaller because of reduced contrast.

Finally, a similar target was placed in a vacuum evaporator and a .0005" thick layer of natural lithium was deposited on the radiation incident surface. This was followed by an overlay of aluminum to protect the lithium from initial oxidation and decomposition upon exposure to the atmosphere. This was then covered with a thin layer of Vac Seal, a polymer, for long time protection. This target was then mounted on a vidicon gun and sealed with a glass plate. Upon exposure to a neutron flux of 100 \( \text{cm}^2\text{sec}^{-1} \) no interaction of product alpha or triton particles in the target was evident.

The absence of observable flashes on the TV monitor could be the result of one of the following. (1) The neutron conversion rate is smaller than expected or (2), the charge collected by the radiation sensitive diodes is too small to be measurable.
The neutron conversion efficiency for a 0.0005" natural lithium layer is 0.4% as given in Appendix C along with other forms of lithium. The product of the neutron flux, the fraction absorbed in the converter and the displayed target area gives the expected rate of flashes to be observed on the TV monitor providing the target is both alpha and triton sensitive. This amounts to $100 \times 0.004 \times 1.3 = 0.52$ per second or very nearly one flash every two seconds. The TV screen was examined for flashes for approximately 1/2 hour. If the minority carriers were collected by the diodes from the interaction of either particle with the same efficiency as for the alpha particles from Am$^{241}$ the observed flashes would have been about $1/2$ Am$^{241}$ intensity and therefore, visible above the monitor background noise level. Since there is no reason to suspect a gross error in the thermal neutron flux measurement obtained with a Victoreen neutron dosimeter, it can be concluded for the moment, that insufficient minority carrier charge was collected.

Insufficient charge collection can result from three causes for the case being considered. These are: a) the particular target employed did not have a response characteristic of the best obtainable sensitivity$^{(7,8)}$, b) the charge reaching the diode surface of the target by diffusion from the ionization track of the short ranged alpha particle was too low, c) the deposited charge from the penetrating triton was sufficiently below the target sensitivity.
A theoretical investigation is required at this point to intelligently discuss the problem of insufficient charge collection. The following chapter discusses this matter further along with pertinent analysis of the Am$^{241}$ results. Conclusions with regard to neutron imaging will therefore, be made following the analysis.

2.4 Conclusions

The results obtained in the experimental work discussed above show definitely that these targets can be used to record a variable spatial distribution in an alpha particle flux. The variation can be caused, as was shown in this work, by imposing a thin object to be studied in a uniform alpha flux resulting in a radiographic display. Further, the position sensitivity of the image tube can be easily adapted to a pin-hole camera for recording the spatial distribution of a charged particle source.
CHAPTER III
THEORETICAL DISCUSSION

The total number of generated electron-hole pairs in the silicon target by individual alpha particles of energy greater than 0.1 MeV is sufficient to provide a video signal\(^{(7,8)}\). It is through understanding of the behavior of generated electron hole pairs from an energetic alpha particle interaction with the target material that the image tube junction array can be properly designed and constructed or its response understood. Therefore, it is the object of this chapter to investigate alpha particle interaction within the base region or zero field region of the target and relate this to the operation of the vidicon tube.

3.1 Diffusion of Induced Minority Carriers from an Alpha Particle Track

The video signal from an individual alpha interaction in the diffusion region of the vidicon target will depend on the fraction of minority carriers which diffuse away from the ionization track and reach the inner diode surface. Since the targets constructed for this work did not include a diffusion of phosphorous on the window side of the image tube, which would have decreased recombination of
minority carrier flow from the bulk, surface states of this unguarded surface are assumed to serve as a sink for minority carriers. Also, since the junctions on the inner surface are also sinks for minority carriers symmetry exists on either side of the mid-plain of the base region for uniform excitation. To be solved first, is the case of an alpha particle from Am^{241} incident on a target 25 x 10^{-4} cm thick.

As shown by Equation (D-1) in Appendix D, the maximum energy transferred to electrons through the principle mechanism of energy loss, ionization, is approximately 3 keV. This maximum electron energy corresponds to a maximum electron range of about 0.1 micrometers for the incident 5.5 MeV alpha particles. The approximate result is a minority carrier cylinder 0.2 micron in diameter and extending in length a distance equal to the alpha particle range. Since the minority carriers have a diffusion length greater than 0.2 micron and in general, interest would be for alpha particles, having a range much greater than 0.2 micron, the initial minority carrier spatial distribution can be considered as a line charge. The total number of charge pairs generated by the energetic alpha particle along its path is given by \( N = E(\text{eV})/3.6 \) as may be found throughout the literature.

It is of interest to obtain an estimate of the induced minority carrier density along the particle path. Assuming that ionization is uniform along the path, which is not entirely true as described by Evans\(^{(13)}\), we obtain for a 5.5 MeV alpha particle having
a range, as given in Appendix D, of 29 microns a minority carrier
volume density of \( \frac{5.5 \times 10^6}{3.6}/\pi (0.1 \times 10^{-4})^2 \ 29 \times 10^{-4} = 10^{18} \) carriers/cm^3. This is indeed a high level for "minority carrier"
density and because of pair generation it is also the concentration
of excess majority carriers which dominates the equilibrium majority
carrier concentration of \( 5 \times 10^{14} \) cm\(^{-3}\).

The effects on transport properties due to the high carrier
density along a particle track is not well understood theoretically
because of the high rate of concentration decrease by diffusion away
from the track. Treatment of lifetime and diffusion coefficient has
been given by Blakemore\(^{(14)}\) and Jonscher\(^{(15)}\) for instantaneous uniform
bulk generation which does not consider a net concentration loss by
diffusion. Also, they give a limited discussion of planar high level
injection which is not the same as for an approximate line source.
For these injection conditions, Blakemore shows that the lifetime
can increase or decrease with injection level for recombination
through material flaws, depending on the initial state of the material.
The diffusion coefficient approaches the ambipolar value \( D \) for high
injection levels where, \( D = \frac{D_e D_h}{D_e + D_h} \); \( D_e \) and \( D_h \) being the elec­
tron and hole diffusion coefficients. Due to the lack of knowledge
about recombination for a high density excess carrier "line charge"
and also the unknown initial condition of the starting material, the
lifetime \( \tau \), will be assumed to be independent of the excess carrier
concentration. Further, the diffusion coefficient is assumed inde­
pendent of concentraion and position. From the point of view of
diffusion, the minority carriers may be treated as being uncharged
and as being the only particle present by making use of the ambipolar
diffusion coefficient.

The continuity equation describing minority carrier particle
flow by diffusion may be expressed in the familiar form under the
above assumptions as,

\[ \frac{\partial C}{\partial t} = g - \frac{C}{\tau} + D\nabla^2 C \]

(1)

where \( C \) and \( g \) are the space and time dependent hole concentration
and generation rates, respectively. Recall that the range of the
alpha particle is equal to or greater than to the thickness of the
silicon target. The solution for the hole leakage through the sur­
face at \( z = + L \) in Figure 5a where the charge sensitive diodes are
located, for the case of an individual line charge, would require
cylindrical geometry having two space variables, \( z \) and \( r \), as well
as time. A simplification is made by allowing the entire target to
assume the initial minority carrier concentration as shown in
Figure 5b, as suggested by Professor Redmond (private communication),
and examining the amount of charge that diffuses out over an area
equal to that of the cross-sectional area of the initial track, thus
eliminating one space variable.

That this approach is justified may be seen from the
following. Consider a point source of charge at some position in
Figure 5. Schematic of real and assumed excess carrier distribution in the silicon target.
a plane located between \(-L\) and \(L\). The ratio of the charge that leaks out at the diode surface to the charge in the source reaches some value lower than one, asymptotically, as time increases. Any other source in that plain of equal strength would have the same value. The total charge leaking out from all point sources in the plane, would simply be a superposition of the amount from each source. The argument could be carried on until the limiting case of a planar source is reached. The fraction from the planar source which leaks out is equal to the fraction from a point source. Consider now, other planes. A different fraction is obtained but it would be equal to the fraction from any one point in that plane. The given points in each plane could be selected on a line pointing in the direction \(z\), the case of the line source.

No information would be obtained on the distribution of charge leaking out of the surface from an individual interaction. This information is not required for our work. It is assumed to be limited to within a radius equal to the diffusion length.

It will be further assumed that the particle concentration at \(-L\) and \(+L\) goes to zero for time \(t > 0\). This can be done if the mean free path is small compared to the sample dimensions. This is the case, since \(2L\) is typically 25 microns, whereas the mean free path for holes in good quality silicon is about .016 micron.
It will also be assumed that ionization is uniform along the particle path and hence, a uniform planar distribution as shown in Figure 5-C. Although this is not true, with ionization increasing toward the end of the path, diffusion following the interaction will tend to smooth the distribution to a uniform value as well as provide the desired leakage current.

Since the stopping time or the time required to establish the initial distribution is extremely short, approximately $10^{-12}$ seconds, the initial distribution may be considered as an impulse at time $t = 0$. The equation which describes the motion of minority carriers becomes,

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial z^2} - \frac{C}{\tau},$$  \hspace{1cm} (2)

for times greater than $t = 0$. Upon substitution of $C = f(z,t) \exp(-t/\tau)$, the wave equation

$$\frac{\partial f(z,t)}{\partial t} = D \frac{\partial^2 f(z,t)}{\partial z^2}$$  \hspace{1cm} (3)

is obtained. Separating $f$ into space and time dependent terms by letting $f = Z(z)T(t)$ and substituting into Equation (3), we obtain,

$$Z \left( \frac{dT}{dt} \right) = TDV^2 Z,$$

or

$$\left( \frac{1}{T} \right) \left( \frac{dT}{dt} \right) = (D/Z) V^2 Z$$  \hspace{1cm} (4)

Since the left side of Equation (4), is dependent on time only and the right side dependent only on space, both sides may be
set equal to a space and time independent parameter \(- B^2\) giving,

\[
\frac{1}{T} \frac{dT}{dt} = - B^2. \tag{5}
\]

and,

\[
\frac{1}{2V^2} \frac{\partial^2 Z}{\partial z^2} = - B^2 D = - \gamma^2 \tag{6}
\]

The solution to Equation (5), becomes,

\[
T = \exp (- B^2 t) \tag{7}
\]

The coefficient has been ignored since it will be absorbed into the undetermined coefficients in the solution of \(Z\).

The solution to Equation (6) can be expressed as

\[
Z = D \sin \gamma z + A \cos \gamma z \tag{8}
\]

Noticing that the distribution is symmetric about \(z = 0\) since uniform excitation and identical sinks are assumed, and for \(t > 0\), \(Z (\pm L) = 0\) the coefficient \(D\) must be zero giving,

\[
Z = \sum A_n \cos \gamma_n z \tag{9}
\]

where,

\[
\gamma_n = (2n + 1) \frac{\pi}{2L} \quad n = 0, 1, 2 \ldots \tag{10}
\]

giving,

\[
B^2 = (2n + 1)^2 \frac{D}{4L^2} \tag{11}
\]

Hence, the solution for the minority carrier distribution for all time becomes,

\[
C(z, t) = \sum_{n=0}^{\infty} A_n \exp \left[ -(\gamma_n^2 D + 1/\tau) t \right] \cos \gamma_n z \tag{12}
\]
The coefficients \( A_n \) may be obtained using Fourier's Theorem. Letting
the initial distribution be \( C_0 \), a constant for \(-L < z < L\) Equation
(12), becomes for \( t = 0 \),

\[
C(z,t) = C_0 = \sum_{n=0}^{\infty} A_n \cos \gamma_n z
\]  

(13)

Multiplying both sides by \( \cos \gamma_m z \) and integrating between \(-L\) and \(L\),
a relationship is obtained giving,

\[
C_0 \int_{-L}^{L} \cos \gamma_m z \, dz = \int_{-L}^{L} \sum_{n=0}^{\infty} A_n \cos \gamma_n z \cos \gamma_m z \, dz
\]  

(14)

The sum on the right may be taken outside the integral
and noting that \( A_n \) is not a function of \( z \) the right side of Equa­
tion (14), becomes

\[
C_0 \int_{-L}^{L} \cos \gamma_m z \, dz = \sum_{n=0}^{\infty} A_n \int_{-L}^{L} \cos \gamma_n z \cos \gamma_m z \, dz
\]  

(15)

From the orthogonality properties the integral is zero except for
\( \gamma_n = \gamma_m \) or \( n = m \). Therefore, this expression becomes

\[
C_0 \int_{-L}^{L} \cos \gamma_m z \, dz = A_m \int_{-L}^{L} \cos^2 \gamma_m z \, dz = A_m L
\]  

(16)

The left side of Equation (14) yields,

\[
C_0 \left[ \frac{1}{\gamma_m} \sin \gamma_m z \right]_{-L}^{+L} = C_0 \left( \frac{1}{\gamma_m} \right) 2 \sin \gamma_m L
\]
But, \( \sin \left( (2m+1) \pi/2 \right) = (-1)^m \). Changing the index back to \( n \) and equating the results, Equations (16) and (17), the coefficients become,

\[
A_n = 4C_0 \frac{(-1)^n}{(2n+1) \pi} \tag{18}
\]

As a result, the complete solution for the space and time dependent minority carrier distribution becomes

\[
C(z,t) = \left( \frac{4qC_0}{\pi} \right) \sum_{n=0}^{\infty} \left[ \frac{(-1)^n}{(2n+1)} \right] \exp \left[ - \gamma_n^2 D + 1/\tau \right] t \cos \gamma_n z \tag{19}
\]

The total charge which diffuses out of the target to the sink located at \( z = L \) per unit area is given by the expression,

\[
Q = \int_0^\infty J(L,t) \, dt \\
= - D \int_0^\infty \frac{dC(z,t)}{dz} \bigg|_{z=L} \, dt \tag{20}
\]

Therefore,

\[
Q = - \left( \frac{4C_0 D}{\pi} \right) \sum_{n} \left[ \frac{(-1)^n}{(2n+1)} \right] \exp \left[ - \left( \gamma_n^2 D + 1/\tau \right) t \right] \left[ \gamma_n \sin \gamma_n z \right] \bigg|_{z=L} \, dt \tag{21}
\]
Again \( \sin \frac{\gamma_n}{L} = (-1)^n \) and after taking the sum outside the integral, Equation (21) becomes,

\[
Q = \left( \frac{2C_0D}{L} \right) \sum_{n=0}^{\infty} \int_{0}^{\infty} \exp \left[-\left(\frac{\gamma_n^2}{\tau} + 1/\tau\right)t\right] \, dt
\]

\[
= \left( \frac{2C_0D}{L} \right) \sum_{n=0}^{\infty} \frac{1}{\left(\frac{\gamma_n^2}{\tau} + 1/\tau\right)}
\]  

(22)

The summation term may be written as,

\[
\sum_{n=0}^{\infty} \frac{1}{[\left(2n + 1\right)^2 \pi^2 D/4L^2 + 1/\tau]}
\]

\[
= \frac{4L^2/\pi^2 D}{\tau} \sum_{n=0}^{\infty} \frac{1}{\left(2n+1\right)^2 + \frac{4L^2}{\pi^2 D}}
\]

which results in an expression for \( Q \) given by,

\[
Q = \left( \frac{8LC_0/\pi^2}{\tau} \right) \sum_{n=0}^{\infty} \frac{1}{\left(2n + 1\right)^2 + a^2}
\]  

(23)

where

\[
a^2 = \frac{4L^2}{\pi^2 D}\]

(24)

A closed form expression of the summation as given by Wheelon is

\[
\left(\frac{\pi}{4a}\right) \tanh \frac{\pi a}{2}
\]

(16)

Substitution into Equation (23) gives finally,
\[ Q = \left( \frac{8LQ_0}{\pi^2} \right) \left( \frac{\pi}{4a} \right) \tanh \frac{\pi a}{2} \quad (25) \]

It is of interest here to determine the total amount of charge which passes the boundary at \( L \) from an \( \alpha \) particle interaction without regard to the number of target diodes which may be involved. A comparison will later be made of the results of this theoretical analysis published experimental results of a similar nature by Keywell\(^{(17)}\) as a test of its validity. For this purpose, it may be noted that \( C_0 = \frac{Q_0}{AR_\alpha} \) where, \( Q_0 = E_\alpha / 3.6 \), and \( A \) is the average cross-sectional area of the ionized track and \( R_\alpha \) is the alpha particle range. \( Q \), as given in Equation (25) must be multiplied by the average cross-sectional area of the track to obtain the amount of charge transmission per alpha interaction. Upon substitution for \( C_0 \) in Equation (25) and multiplying by \( A \), we note that this rather nebulous cross section cancels out with the result.

\[ Q_\alpha = \left( \frac{8LE_\alpha}{3.6\pi^2 R_\alpha} \right) \left( \frac{\pi}{4a} \right) \tanh \frac{\pi a}{2} \quad (26) \]

Before concluding this section however, it should be noted from Equation (25) that the fraction \( f \), of all charge which leaks out at the boundary \( L \) can be written as

\[ f = \frac{Q}{C_0L} = \frac{(\tanh \frac{\pi a}{2})/\left(\frac{\pi a}{2}\right)} {= \frac{\pi a/2}{(\pi a/2)}} \quad (27) \]

The value of \( f \) is therefore bounded between 1 for small values of \( a \) and 0 for large values of \( a \).
3.2 Collection of Induced Minority Carriers from Am\textsuperscript{241} in a 25 Micron Thick Target

The desire here is to determine from the above developed theory the amount of charge collected from Am\textsuperscript{241} interactions in a 25 micron thick vidicon target since these were the conditions of the experimental work.

All parameters are known in Equation (26), except the value of a. From Eq. (24), \( a = \frac{2L}{\pi \sqrt{D_T}} \) where \( \sqrt{D_T} \) is known by definition as the diffusion length for the minority carriers. Of importance here is to find reasonable values for the diffusion length in silicon for high quality target material and for material used in our experimental work. The first will help in design optimization and predicting device performance and the second will provide useful information in explaining our experimental results.

As mentioned earlier, the effects of high level injection in the form of a line charge on the low level lifetime has been neglected for the reasons stated. Darnaley and Northrop\textsuperscript{(18)} summarize the general belief that initial recombination is rapid but do not give any detailed experimental confirmation. If this be the case however, \( Q \) in Equation (26), would be reduced. Experimental work by Keywell\textsuperscript{(17)} does not show the drastic reduction in charge collection that is inferred and further discussion will be given later.

Values for the lifetime and diffusion coefficient, through the Einstein relationship \( D = \frac{kT \mu}{q} \), were obtained from the literature\textsuperscript{(19)} for high quality 10 ohm-cm n-type silicon and for highly
doped ($10^{18}$ cm$^{-3}$ level) to represent the properties of poorer material comparable to what was used in this work. The reduced quality of the silicon can be due to initially poor material and to methods of preparing the targets prior to the various heat treatments which cause a high density of dislocations and damage; the details of which were discussed in Chapter II. Obtained values were $\tau_h = 10$ $\mu$ sec, $D_n = 32.5$ cm$^2$/sec and $D_h = 12.5$ cm$^2$/sec for the better quality material and $\tau_h = 0.4$ $\mu$ sec, $D_n = 3.25$ cm$^2$/sec and $D_h = 1.63$ cm/sec for the lower quality silicon. The ambipolar diffusion coefficients were 18 and 2.18 cm$^2$/sec, respectively. The respective diffusion lengths become 134 and 9.3 micrometers. The alpha particle range is obtained from Figure 10, Appendix D.

Substitution of known quantities in Equation (26) yields,

$$Q_\alpha = (5.3 \times 10^5) (0.785/a) \tanh 1.57 a$$

For the two materials, parameter a becomes $5.9 \times 10^{-2}$ and 0.86, respectively for the better and lower quality materials. The results for the two cases are:

$$Q_\alpha = 6.5 \times 10^5$$
$$Q_\alpha = 4.08 \times 10^5$$

respectively. Either because of side diffusion or the precise position of the interacting alpha particles, the calculated charge could be distributed between four neighboring diodes on the target.
where typically the diodes are located on 50 micron centers, as discussed in Chapter II. This would reduce \( Q_a \) by a factor of 4 for the charge collected per diode, \( Q_{a,d} \) giving, \( Q_{a,d} = 1.6 \times 10^5 \) and \( 1.00 \times 10^5 \), respectively. Evaluation of Equation (27) gives values of \( f \), equal to 0.997 and 0.647, respectively. For design purpose, Equation (27) may be plotted as \( f \) versus \( a \). A required value of \( f \) may then be determined, based on desired sensitivity, giving a minimum value of \( a \). This will determine \( a/\overline{D_T} \) value which tells how bad a material can be for a given target thickness \( L \).

The results and material parameters of this analysis was summarized in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>( D_n ) (cm(^2)/sec)</th>
<th>( D_h ) (( \mu ) sec)</th>
<th>( D ) (carriers ( \times 10^5 ))</th>
<th>( Q_a ) (%)</th>
<th>( Q_{a,d} ) (%)</th>
<th>( \varepsilon_a ) (%)</th>
<th>( \varepsilon_{a,d} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>32.5</td>
<td>12.5</td>
<td>18</td>
<td>10</td>
<td>6.5</td>
<td>1.6</td>
<td>43</td>
</tr>
<tr>
<td>B</td>
<td>3.2</td>
<td>1.6</td>
<td>2.2</td>
<td>0.4</td>
<td>4.0</td>
<td>1.02</td>
<td>26.7</td>
</tr>
</tbody>
</table>

Included here is the total \( \varepsilon_a \), and diode \( \varepsilon_{a,d} \) collection efficiency at the diode boundary of the silicon vidicon tube target. These efficiencies were determined by dividing \( Q_a \) and \( Q_{a,d} \) by...
$Q_0 = \frac{E_a}{3.6}$ the total possible induced charge in the target. The labeling A and B refer to the 10 ohm-cm high and low quality silicon target materials.

The overall target and out diffusion efficiencies based on total possible induced charge are seen to be 86% and 53% for the two targets. However, eliminating the target efficiency which is due to $R_u$ being slightly greater than $2L$, the effects of recombination within the target becomes more clear. Since $R_u > 2L$, the reduction of $Q$ as presented in Equation (26) becomes $(1 - \frac{2L}{R_u}) = 0.137$ or 13.7%. Therefore, the intrinsic out diffusion efficiencies for an initial minority carrier line distribution having the geometry given becomes 99.7% and 67% for the two material targets. This is, as expected, in agreement with evaluation of the material dependent expression, Equation (27).

Target recombination of charge amounts to only 0.3% for a high quality target but amounts to 33% for our targets. Another way to present the results of these two target materials is to note that recombination is insignificant in one but accounts for a loss of 1/3 of the induced charge in the other. This may be at first glance a somewhat surprising and unbelievable result in view of the assumptions and discussion made concerning the lifetime used in these calculations. However, the experimental work by Keywell$^{(15)}$ mentioned earlier along with his keen sense of analysis can be drawn upon at this point to make these
arguments more plausible. In Figure 10 of his article, he shows a curve giving a back-collection factor as a function of distance from the depletion region edge in a high quality silicon surface barrier radiation detector for incident Am$^{241}$ alpha particles. The back-collection factor as defined is the fraction of pairs (electrons and holes) generated outside of the space-charge region at a position $x$ in length $dx$ which subsequently are collected in the space-charge region. However, only one carrier is active, in producing a signal contribution, this being the minority carrier. Examination of Keywell's graph for the reasonable integration time of 5 $\mu$ sec shows that over the distance from 0 to 12.5 micrometers from the depletion region edge, the average value of experimentally collected charge is 40$\%$ which is in agreement with the above analysis. Indeed, interpretation of his experimental curve for purposes of imaging shows that 10$\%$ of the minority carriers can be collected from those present at a distance of 42 microns and the cut-off point beyond which no charge can be collected by diffusion is 52 microns in the time period of 5 microseconds.

Keywell's results are important from another standpoint in support of the diffusion process. It may be argued that the range of the Am$^{241}$ alpha particle in a silicon target of thickness 25 microns is long enough to cause ionization within the diode depletion region sufficient to obtain a video signal without the requirement of diffusion.
collection. That this is the case is easily shown by, again assuming uniform ionization, multiplying the total charge deposited along the track, \( E_a/3.6 \), by the fraction of the total path length which is in the depletion region. Since the depletion region width for a p-n junction can be found in any semiconductor text book to be equal to \( (1/2) \sqrt{\rho V} \) micrometers, for diffused junctions in relatively high resistivity base material, where \( \rho \) is the base resistivity of 10 ohm-cm and \( V \) is the bias voltage, typically 10 volts, the depletion region width becomes equal to 5 microns. Since the alpha range for \(^{241}\text{Am} \) is about 29 microns, the charge deposited in the space charge region of a 25 micron thick target becomes \( 1.5 \times 10^6 \times (5/29) = 2.6 \times 10^5 \) carriers. Basic sensitivity measurements by Harpster and Jacoby\(^7\) for the vidicon target requires a minimum of \( 6 \times 10^3 \) carriers per diode to produce an observable signal. Therefore, the amount of charge deposited directly in the space charge region of a thin vidicon target from a penetrating alpha particle is sufficient to produce a video signal. However, it should be noted that the chance for direct diode depletion region interaction is reduced by a factor of 1/4 from that of diffusion collection since one diode area is approximately 1/4 that of the total target area. Source and geometry considerations in Appendix B predict 32 interactions per frame sweep. Experimental observations are 25 interactions per frame sweep as given in Chapter II instead of 8 per frame sweep implied if only direct deposition was responsible for the video signal.
3.3 Requirements for Neutron Imaging Using an (n,α) Convecter.

Since attempts were made to obtain a video signal generated by the 2 MeV alpha particles from a vacuum evaporated natural lithium converter layer on the targets used for the detection of Am$^{241}$ alpha particles as discussed in Chapter II, an analysis will be made here of this arrangement. As a result, recommendations will be made with regard to target design requirements including the converter layer which will make possible a neutron sensitive image tube.

The system to be analyzed is shown in Figure 6. Of primary importance is a determination of whether or not the collected charge on the diode surface of the target is sufficient for a video signal from an alpha particle initiated at the lithium-silicon interface and traveling in the z-direction. Discussion will later be made of the neutron conversion efficiency in the converter layer under the constraint that the converter thickness be more than 75% of the alpha particle range in the converter. Discussion will also be concerned with utilizing the triton product particle in the Li$^6$(n,α)$^3$H reaction; the reaction energy Q being split between the alpha and triton with $E_\alpha = 2.05$ MeV and $E_T = 2.72$ MeV.

The initial distribution of charge as discussed in Section 3.3 is as shown in Figure 6b where u represents the maximum range of the alpha particle from the converter. As before, the substitution of $C = f(z,t) \exp (-t/\tau)$ is made in Equation (2) and after separating
Figure 6. Schematic of real and assumed excess carrier distribution in the silicon target for neutron conversion.
variables by letting \( f(z,t) = Z(z)T(t) \) solutions of the form of Equation (7) and (8) are again obtained. Equation (7) again stands as it is; however, due to the shift of the origin Equation (8) is changed. Since \( Z = 0 \) at \( z = 0 \), \( A \) must be zero, and since \( Z = 0 \) at \( z = w \) for all time, \( \sin \gamma w = \sin \pi n = 0 \). Therefore \( \gamma_n = n\pi/w \) where \( n = 1,2,3... \) and since \( B_n^2 = D\gamma^2 \) then, \( B_n^2 = D\gamma_n^2 \). The solution to this problem therefore, becomes

\[
C(z,t) = \sum_{n=1}^{\infty} A_n \exp \left[-(\gamma_n^2 D + 1/\tau)t\right] \sin \gamma_n z
\]

Again the coefficients may be obtained using Fourier's theorem. Letting the initial distribution \( C(z,0) \) be \( C_0 \) for \( 0 < z < u \) and \( C(z,0) = 0 \) for \( u < z < w \). After multiplying by \( \sin \gamma_n z \), integrating, and applying the orthogonality relationship on the right hand side, the result is found:

\[
\left. \left( C_0 w/n\pi \right) \cos \gamma_n z \right|_0^u + 0 = A_n w/2
\]

providing the coefficients,

\[
A_n = \left(2C_0/n\pi\right) \left(1 - \cos \gamma_n u\right)
\]

Hence, the space and time dependent solution becomes

\[
C(z,t) = \left(2C_0/n\pi\right) \sum_{n=1}^{\infty} \frac{(1/n)}{(1-\cos \gamma_n u)} \sin \gamma_n z \exp \left[-(\gamma_n^2 D + 1/\tau)t\right]
\]

To obtain the amount of charge leakage per unit area at \( z = w \),
Equation (20) is again employed giving,

$$Q_{z=w} = 2C_0D/W \left[ \sum_{n=1}^{\infty} (-1)^n (\cos \gamma_n u)/(n^2+a^2) \cdot r - \sum_{n=1}^{\infty} (-1)^n/(n^2+a^2) \cdot r \right]$$

(30)

where,

$$r = D\pi^2/w^2$$

(31)

and,

$$a^2 = w^2/\pi^2 D$$

(32)

Finally, after factoring out $1/r$,

$$Q_{z=w} = (2C_0D/\pi^2) \left[ \sum_{n=1}^{\infty} (-1)^n (\cos \gamma_n u)/(n^2+a^2) - \sum_{n=1}^{\infty} (-1)^n/(n^2+a^2) \right]$$

(33)

From Wheelon (16) the second sum term can be expressed as,

$$\sum_{n=1}^{\infty} (-1)^2/n^2 + a^2) = (\pi/2a)\text{csch } \pi a - 1/2a^2$$

(34)

The first summation term cannot be obtained in closed form. Substitution of parameters, however, showed rapid convergence for this term and a computer was used to sum up to $n = 100$. For the two materials having transport properties of $A$ and $B$ of Table 1, the result of this summation was $-0.602$ and $-0.302$, respectively. Evaluation of Equation (34) alone gave values of $-0.823$ and $-0.364$ for the respective materials. Thus, the modifying bracketed term in Equation (33) was $0.221$ for target material $A$, and $0.062$ for the poorer material $B$, used in the experimental work.
Table 2, summarizes the results of the complete evaluation of $Q_{\alpha,d}$, the charge collected per diode from the Li$^6(n,\alpha)T^3$ reaction under the geometry shown in Figure 7. The loss due to the sink on the radiation side of the target where the initial charge track exists is overwhelming, accounting for perhaps more than 80% of the induced carriers. The region between u and w in Figure 7 acts, as would be expected, as a diffusion impedance region with regard to desired collection at the position w by the diodes.

We conclude that a video signal can not be obtained for these short ranged alpha particles using targets that are degraded in transport properties from the best obtainable for the geometry examined. The absolute minimum number of carriers needed to detect a video signal from background noise is $6 \times 10^3$ as discussed in Section (3.2). This absolute minimum was determined on a target

<table>
<thead>
<tr>
<th>Material</th>
<th>$Q_{\alpha,d}$ Carriers x 10</th>
<th>$\epsilon_{\alpha,d}$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$21 \times 10^3$</td>
<td>4%</td>
</tr>
<tr>
<td>B</td>
<td>$5 \times 10^3$</td>
<td>1%</td>
</tr>
</tbody>
</table>

TABLE 2. CHARGE COLLECTION PER DIODE FROM Li$^6(n,\alpha)T^3$ ALPHA INTERACTION ON A 25 MICRON THICK TARGET
which was the better of nearly 45 targets constructed by Harpster and Jacoby (7) using infrared and x-ray fluxes and is in agreement with others (6) who were concerned with these measurements. Therefore, only the best target material having the properties of material A in Table 2, with a target thickness of 25 microns would stand a chance as being useful as a vidicon tube target in these measurements. The material labeled B would not allow sufficient charge collection for a discernible signal.

With regard to the possibility of the triton interacting in a 25 micron silicon target of material B to produce a video signal, it is noted first from Evans (13) that the range of a triton of energy three times that of a proton, \( E_p \) is just three times the range of the proton of energy \( E_p \) or,

\[
R_t(3E_p) = 3 R_p(E_p) \tag{35}
\]

From the Bragg-Kleeman rule the range of the proton of energy \( E_p \) can be obtained from range data in air as given in Evans (13) for heavy charged particles as,

\[
R_{psi}(E_p) = 3.2 \times 10^{-4} \ 28/2.33 \ R_{air}(E_p) \tag{36}
\]

The energy of the triton being 2.71 MeV requires finding the range of a proton of energy 0.91 MeV to obtain the range of the triton. This is found to be very nearly 12.5 microns.
The range of the triton becomes therefore, 37.5 microns in silicon. Since this is much larger than the thickness of the silicon target an estimate must be made regarding the specific ionization or ion pairs created per micron of the initial part of the triton path. Since the specific ionization is proportional to the square of the incident particle charge the ionization will be, very approximately, 1/4 that of an alpha particle. From another graph in the article by Keywell\(^{(17)}\) the initial average ionization per micron for alpha particles in silicon is given to be \(4.5 \times 10^4\) resulting in an average initial value for the triton of \(1.1 \times 10^4\) ion pairs/micron. Multiplying by 25, the number of micrometers in the target thickness, and by the collection efficiency for the initial uniform target distribution of 8% a value for the number of possible charges collected is obtained, \(22 \times 10^3\) carriers.

A triton can also originate on the outward surface of the lithium layer of 12.5 microns thick. Computations show very approximately that the effective stopping power of lithium over silicon is \(37/60\) or 0.62. Therefore, the silicon equivalent thickness of the lithium layer is about \(12.5 \times 0.62 = 7.7\) micrometers. The total absorber thickness becomes \(25 + 7.7 = 33\) micrometers which is still less than the range of the triton. This however, does boost the average linear ionization density which becomes \(1.5 \times 10^4\) ion pairs/micron. This increases the number of collectable charges to \(30 \times 10^3\).
The larger of these two is 5 times the minimum required to provide a video signal in the most sensitive targets. Since targets can vary in sensitivity due to target surface oxides and electron beam deposited organics on the diode surface, material defects and surface damage, it cannot be argued from the above values that a signal should have been observed.

However, if the depletion region thickness is 5 microns as discussed earlier, the penetrating triton with a specific ionization of $1.6 \times 10^4$ ion pairs/micron at the position of the diodes should deposit $80 \times 10^3$ carrier pairs directly in the depletion region. Although, this is less than 1/3 that calculated for the Am$^{241}$ it should be sufficient to obtain a visual flash on the monitor.

However, as presented earlier in the discussion of Am$^{241}$ the interaction rate is reduced by a factor of 1/4. Further, since only the triton is being considered, slightly less than 1/2 of them are travelling out of the converter in the direction of the target. Combining these the predicted time between expected interactions is increased from 2 seconds, as presented in Chapter II, to 16 seconds.

3.4 Conclusions

This chapter has presented a theoretical discussion of alpha interactions within the silicon target. Both 5.5 MeV alphas from Am$^{241}$ and 2.0 MeV alphas from a neutron converter layer were considered. It was shown for the case of Am$^{241}$, that charge
collection by diffusion of minority carriers produced in the zero field base region of the target was sufficient to account for the observed video signal. It was further shown that direct deposition of charge in the diode depletion region was sufficient to generate an observable video signal but the rate of observation would be reduced by $1/4$ over that for the diffusion process. Comparing the computed target interaction rate with observed interaction rates did not show reduction. It can be concluded therefore, that although both processes can contribute to a video signal, the diffusion mechanism alone of charge collection is adequate as a signal producing interaction.

It was further shown from theory that neutron interactions in the experimental converter layer could not be observed by means of the alpha produced ionization in the silicon target since for this case the target was too thick. Based on the specific ionization of the longer ranged triton particle originating from two extreme positions in the converter, only $5$ times the minimum required charge to produce a signal in our most sensitive target is collected. Since this is within the estimated order of magnitude error in target sensitivity measurements, it can not be concluded that a signal should have been observed. It was further shown that direct deposition of charge within the depletion region was sufficient for a video signal but the estimated interaction rate was
reduced by a factor of 1/8 giving an estimated 16 seconds between flashes. Background scintillations on the monitor may have prevented visual discrimination of these presumably weak interactions if they were present.

Finally, targets having a thickness equal to the range of the alpha particle from the reaction \( \text{Li}^6(n,\alpha)\text{T}^3 \) can unquestionably be used to measure a single reaction produced alpha particle on a TV monitor. Further, it is possible with good material targets having high sensitivity or high minority carrier collection efficiency to construct a target of appropriate thickness to have both alpha and triton particle sensitivity.
CHAPTER IV

DISCUSSION AND CONCLUSIONS

The research reported in this dissertation presents for the first time an experimental demonstration of vidicon alpha particle imaging, a theoretical approach to the analysis of target response to individual alpha particles, and a theoretical description of a useful new neutron imaging tube.

Although the type of tube used in this work has previously been employed for optical and x-ray imaging, this research represents a direct application of these tubes to a totally different area. This research also represents very nearly a conclusion to more than three years of work to present definitively the broad usefulness of these image tubes. Applications now include the optical and IR range of the electromagnetic spectrum, x- and gamma-rays, charged particles, and neutrons. It remains, however, as a challenging exercise to show an experimental demonstration of neutron imaging.

The experimental results using an Am$^{241}$ source were conclusive from the standpoint of providing a TV displayed image. The video response was shown theoretically to be dependent on alpha particle energy for alpha particles having a range less than the target thickness. It was determined that alpha particles of energy
near 2 MeV and below could not be electrically detected in the video camera with present targets of approximately 25 microns thickness.

Refinement in target geometry to obtain fully depleted targets would enable 100 percent collection efficiency of induced carriers. For protons or alpha particles, the resulting image tube would provide space and energy resolution useful in the study of defects and the migration of impurities along channel directions in thin material samples. Further, a real time gray scale becomes a possibility by utilizing an appropriate incident flux level. Cooling targets to liquid nitrogen temperatures would improve the energy discrimination qualities of the image tube, thus opening a new area of direct application.

In order to obtain increased collection efficiency from the target, a second diffusion of a high concentration of n-type impurity should be made on the radiation incident surface. This would very nearly double the response from 25 microns thick targets for Am$^{241}$ by greatly reducing the loss at this surface sink and aid diffusion by providing a drift field. Drift fields may be as good as a fully depleted layer if the base width $w < \sqrt{dr}$. This step alone would most probably suffice for experimental confirmation of neutron imaging using a lithium converter.
APPENDIX A

OXIDATION AND PHOTORESIST PROCEDURE

Lap and Polish slices

Preclean

1. Swab with TCE.
2. Swab with methanol.
3. Swab with acetone.
4. Dry in \( N_2 \).
5. Immerse in HF for 2 minutes.
6. Rinse with distilled \( H_2O \) (avoid exposure to air until clean).
7. Rinse in hot \( H_2O \).
8. Suspend in hot \( HNO_3 \) (80°C) for 10 minutes.
   (Ultrasonically agitate solution for at least 5 minutes.) Decant acid, rinse with \( H_2O \).
9. Rinse in hot \( H_2O \) for several minutes to remove all traces of acid.
10. Dry and store in \( N_2 \) atmosphere.

Oxidize

1. Place slice in steam fed oxidation furnace until desired oxidation thickness is reached, as shown in Figure 7.
Figure 7. Oxide thickness as a function of time.
Photoresist Technology

Preclean

1. Swab in TCE.
2. Boil two minutes in TCE.
3. Rinse in methanol and dry by evaporation.
4. Rinse in acetone.
5. Bake five minutes in \( \text{N}_2 \) atmosphere at 150°C.

If slices must be stored; immerse in acetone and bake in \( \text{N}_2 \) at 150°C (5) just prior to KPR application.

KPR Application

1. Dip in 60% KPR - 40% KPR thinner solution and dry (2 micron film) or,
   Spin on 60-40 solution at 1800 rpm (approximately 30 sec.) for 1/2 micron film.
2. Dry 30 minutes at room temperature in dark (no uv).

Exposure

1. Align mask on slice and keep mask flat against slice.
2. Expose to ultraviolet light for 4-6 minutes.

Develop Mask

1. Develop for 5 minutes in KPR developer.
2. Rinse for 15 seconds using squirt bottle of methanol.
3. Rinse for 15 seconds in ether using squirt bottle and dry in \( \text{N}_2 \) for ten minutes.
Baking

1. Bake slices 30 minutes at 130°C-220°C in N₂ atmosphere.

Etching Solution - 1000 Å SiO₂/min.

1. Dissolve 20 g NH₄F in 30 ml distilled H₂O.
2. Filter through coarse Whatman #1 paper.
3. Add 5 ml HF (48°-49°) reagent grade per 32 ml NH₄F solution.
4. Store in polyethylene bottle at room temperature.

Etching Procedure

1. Use mechanical agitation.
3. Etch 2-1/2 minutes past color removal which occurs at 2100 Å.
4. Do not contaminate etching solution with any oxidizing reagent.
5. Rinse slice thoroughly in distilled H₂O (do not expose to air until completely clean).

KPR Removal

1. Boil slice 3 minutes in TCE.
2. Swab with TCE.
3. Boil slice 2 minutes in TCE.
4. Prior to diffusion soak slice 10 minutes in ultrasonically agitated H₂SO₄ at 80°C and rinse in H₂O.
APPENDIX B

PROBABILITY OF TWO-ALPHA INTERACTIONS

The analysis to follow considers the probability of having two alpha particles, emitted from a 1 micro Curie Am$^{241}$ source, interacting with one of the target diodes within one target sweep period, thus giving rise to the observed video signals. Information on the Am$^{241}$ source distribution is unknown and has been neglected. The source is however, confined to an area of approximately 6mm$^2$ in the center of the holder and is located 2 cm from the face of the target in vacuum.

The region of the target being scanned by the vidicon tube beam measures 1 cm by 1.3 cm giving 1.3 cm$^2$ area. With a target diode density of 25 x 10$^4$ diodes/in.$^2$, this amounts to 5 x 10$^4$ diodes upon which the Am$^{241}$ alpha particles can randomly interact.

The area of the sphere of radius 2 cm about the source is 50.2 cm$^2$. Therefore, the number of alpha particles interacting with the effective target area per second is $3.7 \times 10^4 \times 1.3/50.2 = 960$ α particles/sec. Since the target is swept every 1/30 sec, there are 32 alpha particles interacting with the sensitive portion of the target per picture frame.
Let \( n = 5 \times 10^4 \) be the total number of diodes available and \( r = 32 \) be the number of interacting particles incident on the diodes in the time span of interest, 1/30 sec. There are \( n^r \) possible arrangements of placing the \( r \) individual alpha particles at \( n \) diode positions each arrangement having a probability \( n^{-r} \).

The number of ways to select groups of \( k \) alpha particle from a total of \( r \) is given by \( r(r-1)...(r-k+1) \) of which there are \( k! \) permutations in each selected group. Therefore, there are \( \frac{r!}{(r-k)!} \) distinguishable ways of selecting groups of \( k \).

To find the probability \( p_k \) that a specified diode will be interacted within one frame sweep by \( k = 2 \) alpha particles, we note that after picking the \( k \) particles in \( \binom{r}{k} \) ways, the remaining \( r-k \) particles interact with the remaining \( n-1 \) diodes in \( (n-1)^{r-k} \) ways. It follows that,

\[
p_k = \binom{r}{k} n^{-r} (n-1)^{r-k} = \frac{r!}{k!(r-k)!} n^{-k} (1-n^{-1})^{r-k}
\]

Inserting the values given for \( n, r, k \) the probability of having two-alpha interaction with one of the target diodes within the time period of one frame sweep becomes, \( p_2 = 2 \times 10^{-7} \).
For neutron conversion efficiency in a converter layer of
the target structure, a limiting factor is the range of the energetic
product particles in the converter. The analysis will deal with
lithium and the compound of lithium, LiF.

The range of the alpha particle in the converter layer can
be obtained from the Bregg-Kleeman formula Equation D-5, Appendix D,
for Li and LiF resulting in 16.7 and 5.6 micrometers, respectively.
Because of self-absorption, converters thicker than this will not
result in increased observable alpha emission into the charge sensi-
tive portion of the target. Indeed, because of neutron flux decrease
as a function of distance from the neutron incident surface, the ob-
servable alpha flux will be decreased.

For our calculations, the thickness of the converter is
picked to be 75% of the alpha particle range, giving 12.5 and 4.2 mic-
rons for the two converters. Converter efficiency can be obtained
by employing the well known relationship for the fraction of neutrons
absorbed in a thickness x, as, \((I_0 - I)/I_0 = 1 - \exp (- \Sigma x)\) where \(\Sigma\)
is the macroscopic linear absorption coefficient given by \(\Sigma = N_0 \rho \sigma\)
fp/m.w., \(N_0\) is Avogadro's number, \(\rho\) converter density, \(\sigma\) the thermal
neutron capture cross section, \( f \), is the molar fraction of lithium in the target, \( p \) is the ratio of Li\(^6\) to total lithium and m.w., is the molecular weight of the converter. The computational results from these relationships are given in Table 3.

**TABLE 3. CONVERSION PARAMETERS FOR VARIOUS NEUTRON CONVERTERS BASED ON PRODUCT ALPHA PARTICLE TARGET INTERACTION.**

<table>
<thead>
<tr>
<th>Converter</th>
<th>( x = (x/4)R_\alpha ) (microns)</th>
<th>( \Sigma (cm^{-1}) )</th>
<th>% Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li(^6)</td>
<td>16.7</td>
<td>43.6</td>
<td>5.5</td>
</tr>
<tr>
<td>Li(^6)F</td>
<td>5.6</td>
<td>57.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Li(nat.)</td>
<td>16.7</td>
<td>3.23</td>
<td>0.4</td>
</tr>
<tr>
<td>LiF(nat.)</td>
<td>5.6</td>
<td>4.26</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Recall the fact that each interacting neutron generated alpha particle which enters the target has sufficient energy to generate enough minority carriers for a video signal. The number of alpha particles travelling in the direction of the target results in the efficiency shown in Table 3 to be very nearly halved.

Since the alpha and triton separate at very nearly 180° from one another, a thicker target converter can be used along with
a thicker and appropriately designed high quality target. In the manner described above for finding the triton range in silicon, the range in lithium and LiF was calculated to be 45 and 27 microns, respectively. Again, letting the thickness of the converter be 3/4 the range of the triton and making the same computations as above for the alpha particles, Table 4 was generated.

Note that interaction efficiency is trebled due to increased converter thickness.

### TABLE 4. CONVERSION PARAMETERS FOR VARIOUS NEUTRON CONVERTERS BASED ON PRODUCT TRITON PARTICLE TARGET INTERACTIONS.

<table>
<thead>
<tr>
<th>Converter</th>
<th>( x = \frac{3}{4} R_t ) (microns)</th>
<th>( \sum (cm^{-1}) )</th>
<th>% Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li(^6)</td>
<td>45</td>
<td>43.6</td>
<td>17.8</td>
</tr>
<tr>
<td>Li(^{6}F)</td>
<td>20.2</td>
<td>57.5</td>
<td>11.6</td>
</tr>
<tr>
<td>Li(nat.)</td>
<td>45</td>
<td>3.23</td>
<td>1.45</td>
</tr>
<tr>
<td>LiF(nat.)</td>
<td>20.2</td>
<td>4.26</td>
<td>0.86</td>
</tr>
</tbody>
</table>
The primary mechanism for energy loss of alpha particles is ionization and electron excitation of the target atoms due to an interaction with the electromagnetic field of the moving particle. For the case of alpha particles of energy in our range of interest, the rate of energy loss has been calculated. In this Appendix, arguments by several authors (13, 18, 21) will be briefly surveyed.

Analysis using classical kinetics of an incident particle of mass, M, and energy, E, colliding with an electron of mass, m results in a maximum energy transferred to the electron of,

\[ W_{\text{max}} = \left[ \frac{4mM}{(m + M)^2} \right] E \]

or since \( m << M \),

\[ W_{\text{max}} \approx (4m/M)E \]  \hspace{1cm} (D-1)

This relationship is quite suitable for the dominant interactions with unscreened outer shell electrons where the binding energies are small.
For an alpha particle having energies between 1 and 10 MeV, this amounts to an energy of $1 - 10$ KeV, or the order of $10^{-3}$ times the alpha particle energy. Therefore, the alpha particle is not significantly deflected from a straight line path. Calculations of the energy loss per unit path length have been made by Livingston and Bethe\(^{22}\) resulting in the prescription,

$$- \frac{dE}{ds} = \frac{4\pi e^4 z^2 N/mv^2}{B}$$  \hspace{1cm} (D-2)

where $z$ and $v$ are the charge and velocity of the alpha particle and $N$ is the number of absorber atoms per cm\(^3\). $B$, called the stopping number, is the logarithmic function,

$$B = Z \left[ \ln \frac{2mv^2}{I} - \ln (1-\beta^2) - \beta^2 - C_K/z \right].$$

or for the common nonrelativistic case,

$$B = Z \ln \frac{2mv^2}{I} - C_K$$  \hspace{1cm} (D-3)

where $Z$ is the atomic number of the absorber, $I$ is the mean ionization potential of the absorber atoms, and $C_K$ is a correction term which represents the deficit in the atomic stopping number due to the ineffectiveness of $K$ nonparticipating electrons.

Values of $C_K$ range between 0 and 1. A value of I for aluminum is given in Evans\(^{(13)}\) to be 164 eV and would not be much different for silicon.
Note that $B$ will vary slowly with alpha particle energy and very approximately, from Equation (D-2), we see that,
\[- \frac{\text{d}E}{\text{d}S} \propto v^{-2} \propto E^{-1} \]

Figure (8) presents the rate of energy loss for alpha particles in silicon as determined from Equation (D-2).

The range, $R$, of a particle is given by the integral
\[ R = - \int_{0}^{v} \frac{\text{d}E'}{(\text{d}E'/\text{d}S)} = \frac{(mM/4\pi e)^2 Z^2 N}{(v')^3 \alpha v'/B(v')} \quad (D-4) \]

The result is in good agreement with experiment for alpha particle range measurements in air as shown on page 650, of reference (13) and shown in Figure 9 over the range of interest.

To a good approximation, within ± 15 percent, the Bragg-Kleeman rule can be used to obtain the range of alpha particles in a given material from known range data in another. Based on an observation that the effective atomic stopping power was approximately proportional to the square root of atomic weight of the material and using the range of alpha particles in air, the range in silicon may be obtained from the Bragg-Kleeman result,
\[ R_s = 3.2 \times 10^{-4} \left( \sqrt{A/\rho} \right) R_{\text{air}} \quad (D-5) \]
\[ = 7.26 \times 10^{-4} R_{\text{air}} \]
Figure 8. Rate of energy loss for alpha particles in silicon as a function of alpha energy.
Figure 9. Range-energy relationship for alpha-rays in dry air at 15°C and 760 mm Hg.
where $A$ and $\rho$ are the atomic weight and density of silicon. From this relationship Figure 10 was constructed showing the range of alpha particles of different energies in silicon. The points for the $(n,\alpha)$ reactions of lithium and boron and for the alpha particles from $^{241}\text{Am}$ have been marked since these are referred to in the main text.
Figure 10. Range-energy relationship for alpha-rays in silicon.
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