RICE UNIVERSITY

MEASUREMENTS OF THE TEMPERATURE DEPENDENCE OF ELECTRON-HOLE PAIR CREATION IN SILICON NUCLEAR RADIATION DETECTORS

by

James Roy Key

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

Thesis Director's Signature:

Thomas A. Rabson

Houston, Texas
May, 1967

MEASUREMENTS OF THE TEMPERATURE DEPENDENCE

OF ELECTRON-HOLE PAIR CREATION IN SILICON

NUCLEAR RADIATION DETECTORS

by

James Roy Key

ABSTRACT

The semiconductor radiation detector may be looked upon as a solid-state ionization chamber in which the energy of incident radiation is dissipated, resulting in the creation of electron-hole pairs in the detector medium.

The purpose of this thesis was to measure ε as a function of temperature, where ε is the average energy required to create an electron-hole pair in a silicon detector. If these devices are to be used to make absolute measurements of particle energy, it is imperative to know the value of ε .

Experimentally, the response of a detector to radiation was observed as a voltage pulse height. The pulse height displayed a repeatable dependence on detector temperature. The pulse rise time was examined for possible effects of dielectric relaxation. Various corrections were applied to thepulse height to arrive at an absolute value of ε .

The response of a lithium-drift silicon detector to radiation from ThC' α's and Bi^{207} conversion electrons was noted over a temperature range of 20-300°K. It was inferred from experimental

data that from 25°K to 20°K, ε experienced a rapid 33% increase from 3.95 $\pm$ 0.035 e.v. to 5.28 $\pm$ 0.035 e.v.

It was concluded that dielectric relaxation effects were not significant, since the pulse rise time was not temperature dependent.

TABLE OF CONTENTS

INTRODUCTION

Purpose

The detection of nuclear radiation is usually based on the ionization or excitation of the atoms in the detector by incident charged particles. The motion of the ions and electrons then depends on the detector medium and the presence of electric fields. To be practical, a detector must meet several conditions. One of the most important of these is that incident particles liberate a large amount of secondary charge; i.e., a large number of ionizing events should occur. For a given radiation energy, the measure of the number of ionizing events is ϵ, the average energy expended per electron-hole pair ionization. The product of ϵ and the number of ion pairs produced is equal to the total energy of the incident particle. Hence materials with a low ϵ tend to produce a large number of electron-hole pairs for a given incident radiation.

Dodge [4,5] and Emery [8] show a basic disagreement in the measured temperature dependence of ϵ in the cryogenic region. Dodge stated that in non-lithium compensated silicon surface barrier detectors, long dielectric relaxation times are responsible for the apparent change in ϵ at low temperatures. It was suggested by Dodge that Emergy, using lithium-drift surface barrier detectors, had measured something other than a change in ϵ .

The purpose of this paper was to measure ϵ in the temperature region from 20-300°K in a lithium-drift surface barrier detector, with particular emphasis on the possible effects of dielectric relaxation on the measured value of ϵ.

Presentation

The operation of semiconductor radiation detectors is similar to the operation of ionization chambers which use a gaseous detection medium. In both devices a set of electrodes establishes an electric field across a region of low conductivity. Along the track of an incident charged particle, electron-hole pairs are created and subsequently separated by the field. The charge which is not lost due to trapping and recombination is collected at the detector electrodes, where it appears as a current pulse. A charge-sensitive preamplifier integrates this current and gives an output proportional to the charge at the input. To measure the actual current pulse at the detector electrodes, the preamplifier must respond to all the frequency components present in the detector signal. A pulse height analyzer measures the output voltage of the preamplifier.

The rise and fall times of the detector current pulse are affected by dielectric relaxation and trapping effects. The pulse height is reduced by trapping and recombination, which in turn are affected by the detector bias voltage.

Dielectric relaxation affects the detector pulse in the following way. The high electric fields present quickly sweep the charge pairs created in the compensated intrinsic region of the P-I-N detector to the edges of the P-I and I-N interfaces. During this time, the moving charges cause an induced charge to move in the detector electrodes. Any charge which is trapped or lost by recombination no longer contributes to the signal. When the trapped charge is released, it once again makes a contribution to the signal. At the P-I interface, the swept holes are injected into the undepleted P-region as majority carriers, where they form a space charge region. The injected space charge exponentially decays to zero. The characteristic time constant for this decay, τ_o, is referred to as the dielectric relaxation time of the bulk material. (The time constant of the decay to equilibrium of the increased carrier distribution is called the recombination time, τ_r, and $\tau_r \gg \tau_o$).

During the period in which space charge neutrality is restored to the detector, the flow of the disturbed charge carriers induces currents in the detector electrodes. A similar argument holds for the injection of electrons in the undepleted N-region of the detector.

The dielectric relaxation time in each undepleted region may be calculated as follows:

$$\vec{\nabla} \cdot \vec{E} = \rho / \chi\varepsilon_o$$

$$\vec{J} = \sigma \vec{E}$$

$$-\dot{\rho} = \vec{\nabla} \cdot \vec{J}$$

$$= \vec{\nabla} \cdot \sigma \vec{E}$$

$$= \sigma\rho / \chi\varepsilon_o$$

$$\therefore \quad \rho = \rho_o e^{-\sigma t / \chi\varepsilon_o}$$

$$= \rho_o e^{-t/\tau_o}$$

where $\vec{E}$ = electric field

ρ = charge density

$\chi(T)\varepsilon_o$ = dielectric constant

$\vec{J}$ = current density

$\sigma(T)$ = dielectric relaxation time

The dielectric relaxation time is defined as the ratio of the dielectric constant of a material to its conductivity. Equivalently, the time constant is the product of the dielectric constant and resistivity of the material. Dearnaley [3] has pointed out that the undepleted region may be regarded as a parallel RC circuit, where $R = \frac{\rho d}{A}$ and $C = \frac{\chi\varepsilon_o A}{d}$. To explain his results, Dodge [4] used a detector equivalent circuit introduced by F. J. Walter that recognizes this feature of the detector. For a non-lithium compensated silicon detector, Dodge stated that although the model explained his data for these detectors between 24-26°K, it did not give correct results below 22°K.

Since the undepleted P- and N-regions of the detector have different resistivities, there will be two dielectric relaxation times. When the dielectric relaxation time exceeds the fall time of the preamplifier, the pulse height analyzer measures a reduced pulse height, and hence, a reduced charge.

The operation of the detector is largely determined by the detector bias and leakage currents. The number of electron-hole pairs collected as the result of the detection of an incident charged particle must exceed the randomly fluctuating background charge normally present due to the leakage current. The bias voltage determines the strength of the collecting field in the detector, the depletion depth, and the leakage current of the detector.

The ratio of the collected charge to the true charge generated in the detector is known as the charge collection efficiency. It can be shown that the collection efficiency is $= 1/(1 + A/V)$, where V is the sum of the bias voltage and the diode contact potential. (See page 22 of this paper). The collection efficiency includes the effects of trapping and recombination.

To summarize, the rise and fall times of the current pulse into the preamplifier are affected by trapping and dielectric relaxation in the undepleted regions of the detector. The charge collection efficiency contains the effects of trapping and recombination. By varying the bias, the charge collection efficiency can be determined, and the true charge is then known after the collected charge is measured.

It should be evident that all the known factors (other than the dielectric relaxation time) which affect the pulse height may be accounted for by varying the detector bias. There is no known way to correct for the effects of dielectric relaxation time; for that reason it was important to observe the rise time of the pulse to see just what effect, if any, the dielectric time would have.

EXPERIMENTAL APPARATUS

A block diagram of the system is shown in Figure 1. A TMC #0351 lithium drift semiconductor surface barrier detector is located in an evacuated chamber and is exposed to radiation from a known source. The high vacuum insures that there is no energy loss by the radiation between the source and the detector. An Ortec Model 210 Detector Control Unit [9] is used to provide precision bias voltages and to measure the leakage current of the detector.

The signal from the detector goes through a double shielded cable to a Tennelec Model 100B low-noise charge-sensitive preamplifier [12]. The preamplifier output stage, a White follower, drives a 33 foot long coaxial cable. This cable feeds the main amplifier; the cable length was optimized by time domain reflectometry [7]. The type A-61 main amplifier (1.6μs input time constant) drives a RCL 20609 256 Channel Pulse Height Analyzer.

In the analyzer, the Analog-to-Digital converter has lower level and discriminator controls which allow an offset to the channel number versus energy curve. Calibration of the system with a precision double-height pulser gives high accuracy, since only the differential linearity of the A-to-D converter is important. The two pulse heights bracket any desired spectrum channel.

The outputs of the preamplifier and main amplifier were monitored by a Tektronix Type 585 oscilloscope with a Type L plug-in. The detector pulses for α particles were photographed and examined for

System Block Diagram

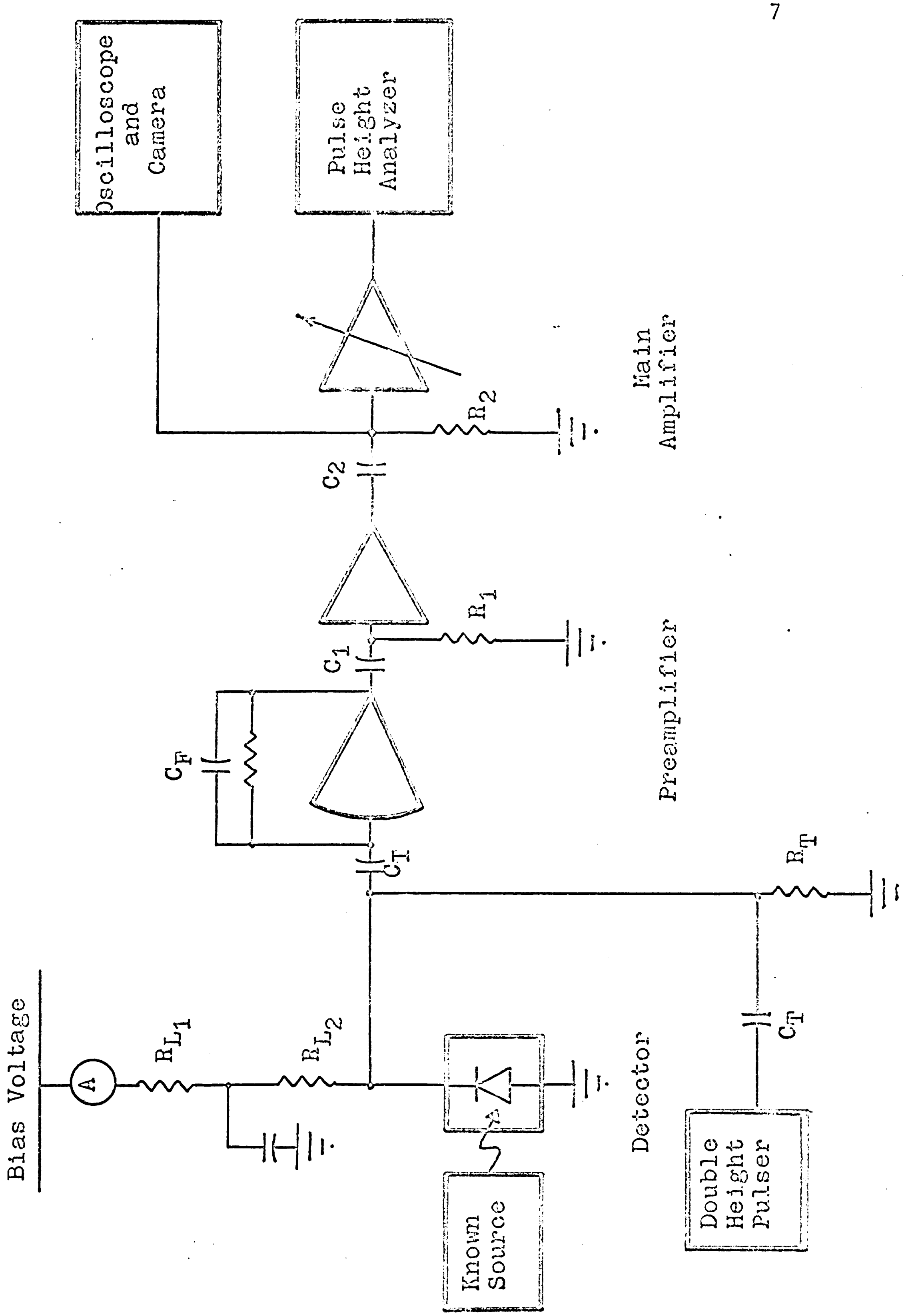
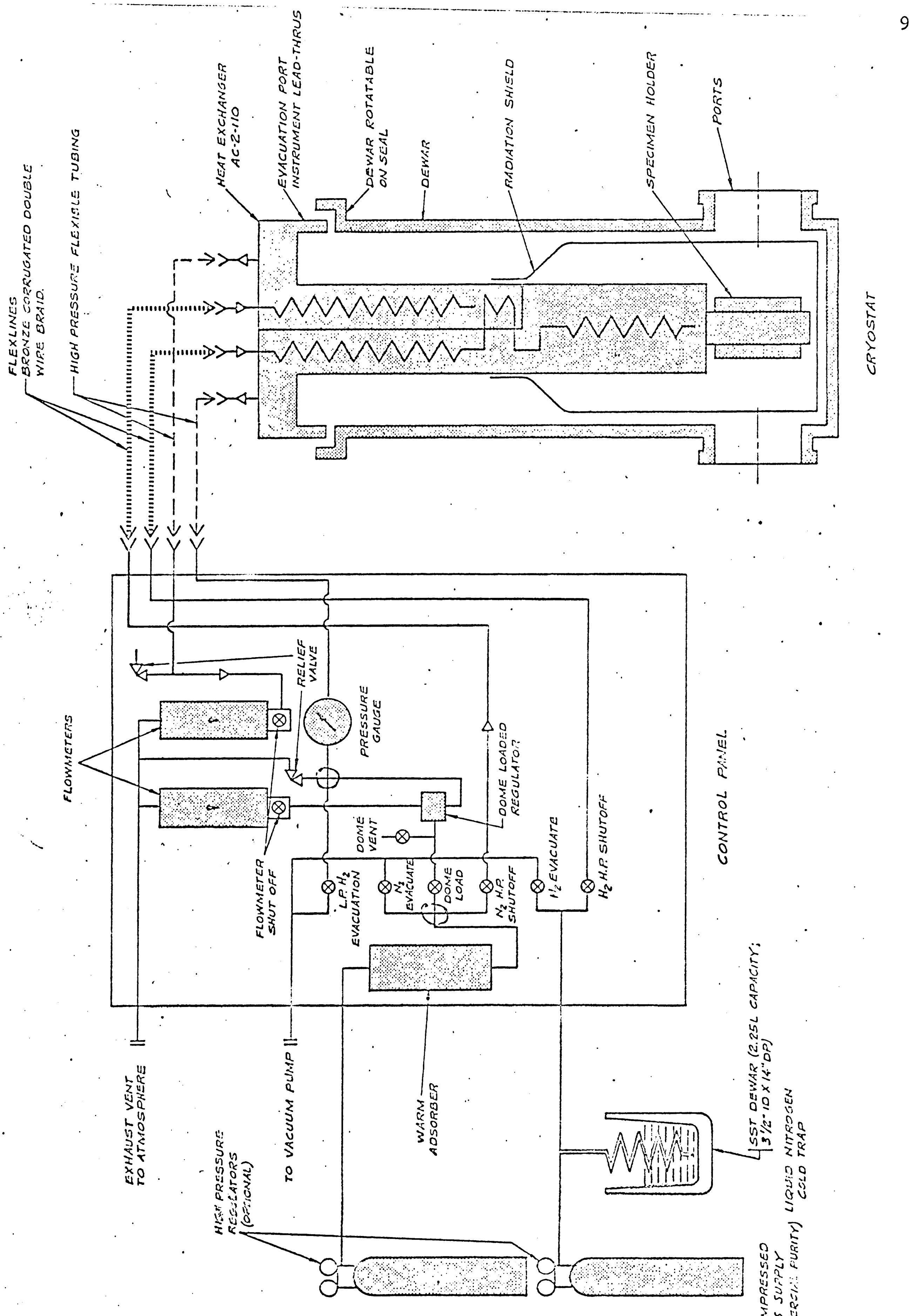


Figure 1

rise time variations with temperature. After none were observed, the detector response to electrons was monitored with the oscilloscope, but no photographs were taken.

An Air Products and Chemicals, Inc. Cryo-Tip [1] holds the detector and source. The detector is mounted to a "cold-finger" which is connected to a heat exchanger. The Cryo-Tip is a miniature, two-fluid, open-cycle, Joule-Thomson refrigerator designed to provide about 5 watts of cooling at cryo-genic temperatures. A schematic of the Cryo-Tip is shown in Figure 2. The temperature of the junction of the detector mount and the "cold-finger" is monitored by a silicon diode thermometer.



Cryo-Tip System Schematic Flow Diagram

Figure 2

EXPERIMENTAL PROCEDURE

Calibration Procedure for Determining the Collected Charge

Source Energy

The sources of radioactive energy were ThC' for α particles and Bi^{207} for conversion electron spectra. The ThC' was collected by exposing demountable tips of electrochemically polished bronze rods to a gas chamber.

The energies of the sources were taken from the data of Strominger, Hollander, and Seaborg [11].

Double Height Pulser

Each test pulser must be capable of supplying a fast rise time step voltage of precisely determinable, variable amplitude. Since the step function is differentiated several times in the electronic chain, the pulse may have an exponential decay, if the decay time is relatively long. The pulser schematic is shown in Figure 3. Capacitor C_p charges for about ten time constants from a known voltage source (V_{total}). This voltage is measured to six significant figures with a Leeds and Northrup Type K3 Universal Potentiometer. The voltage is thus known with accuracy. The voltage source is varied through an ESI Dek-A-Pot with 0.05% linearity. A mercury-wetted contact relay (no contact bounce, fast rise time) dumps the capacitor charge into a resistive voltage divider and charges capacitor C_t (known to five significant figures). Hence the test charge to the preamplifier is known with accuracy.

DOUBLE PULSE HEIGHT CLAIBRATION PULSER

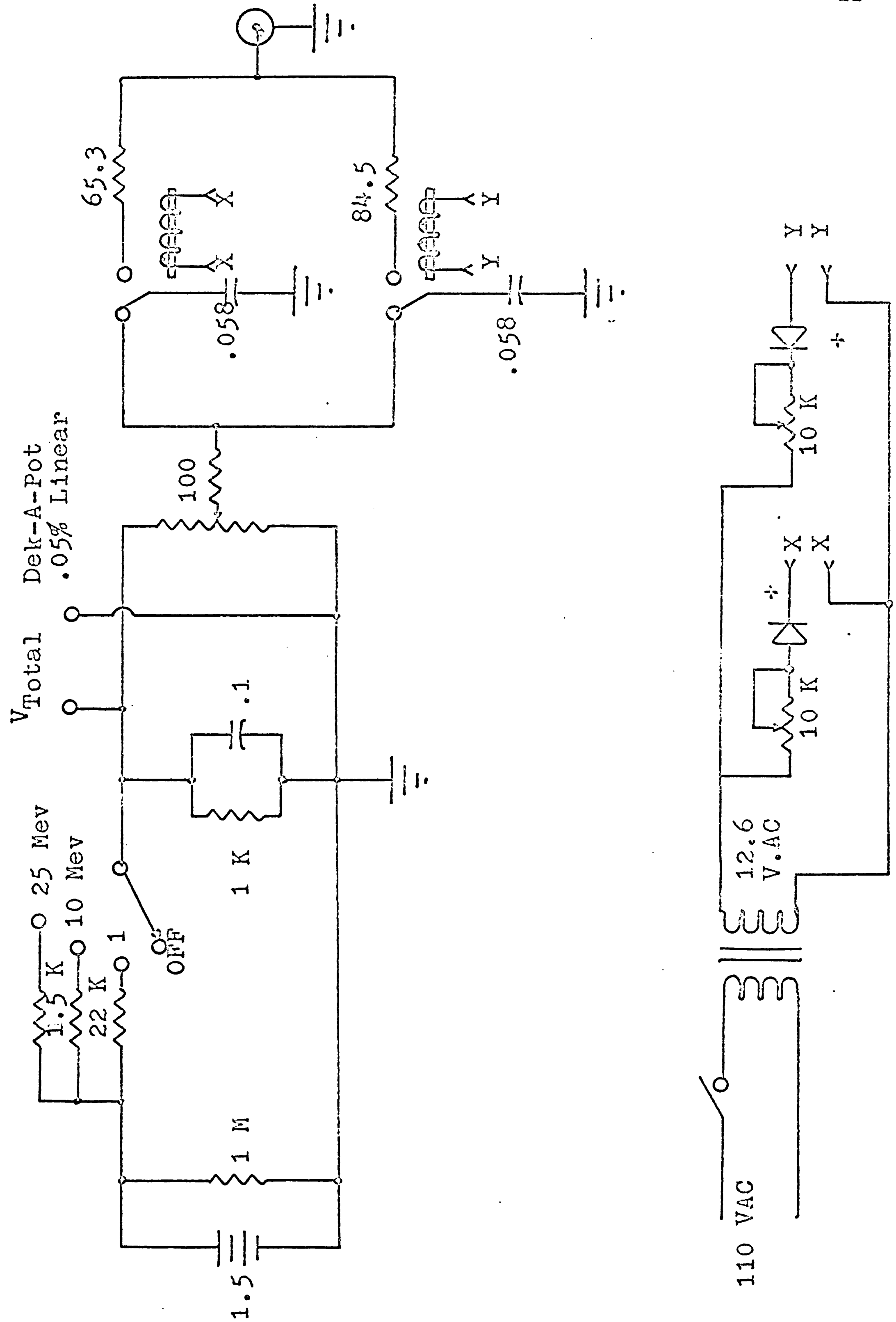


Figure 3

The double height pulser uses two mercury relays which operate sequentially on alternate cycles of a 12 volt 60 cycle power supply. By using a voltage divider, the ratio of the two pulse heights is fixed and may be accurately determined by potentiometric measurements. An analysis of factors such as dielectric relaxation of the capacitor C_p, matching of transmission line impedance with the source and terminating resistors, cable losses and cable capacity, and charge loss during transit time of the mercury relay were fully investigated by F. E. Emery [7].

Temperature Control

It has been shown, both experimentally and theoretically, that the forward voltage of a P-N junction is a reproducible function of temperature [2,10]. The silicon diode thermometer used for temperature measurements was designed and calibrated by Emery [6]. The accuracy of the calibration is within 1°K at cryogenic temperatures. Since the detector is mounted in a copper heat sink, the true detector temperature could not be measured, and the 1°K accuracy was felt to be adequate. The circuit diagram of the silicon diode thermometer is shown in Figure 4. The temperature calibration curve is shown in Figure 5.

Vacuum System

The primary vacuum system consisted of a Welch Duo-Seal mechanical vacuum pump, a small air-cooled diffusion pump, and a liquid nitrogen

SILICON DIODE THERMOMETER

CIRCUIT DIAGRAM

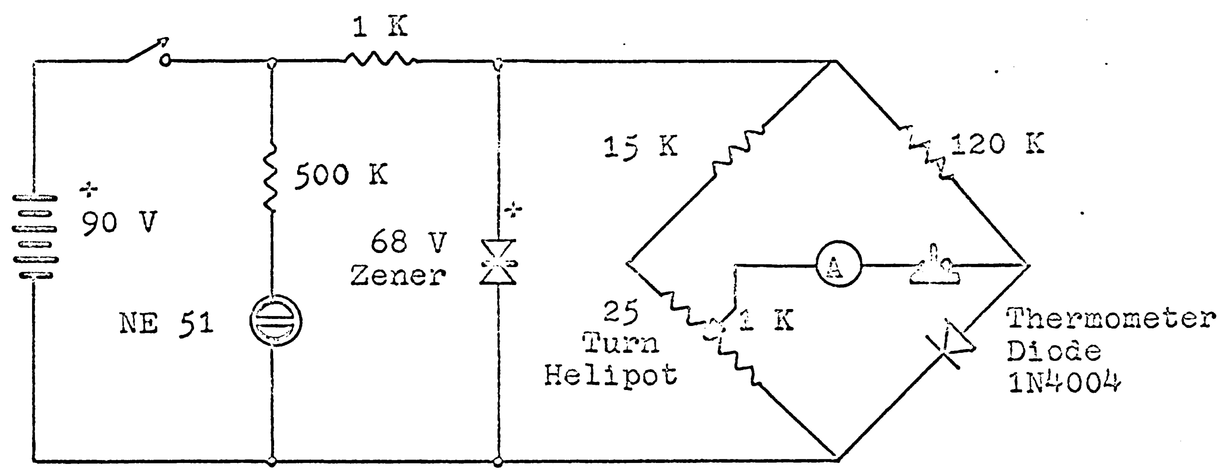


Figure 4

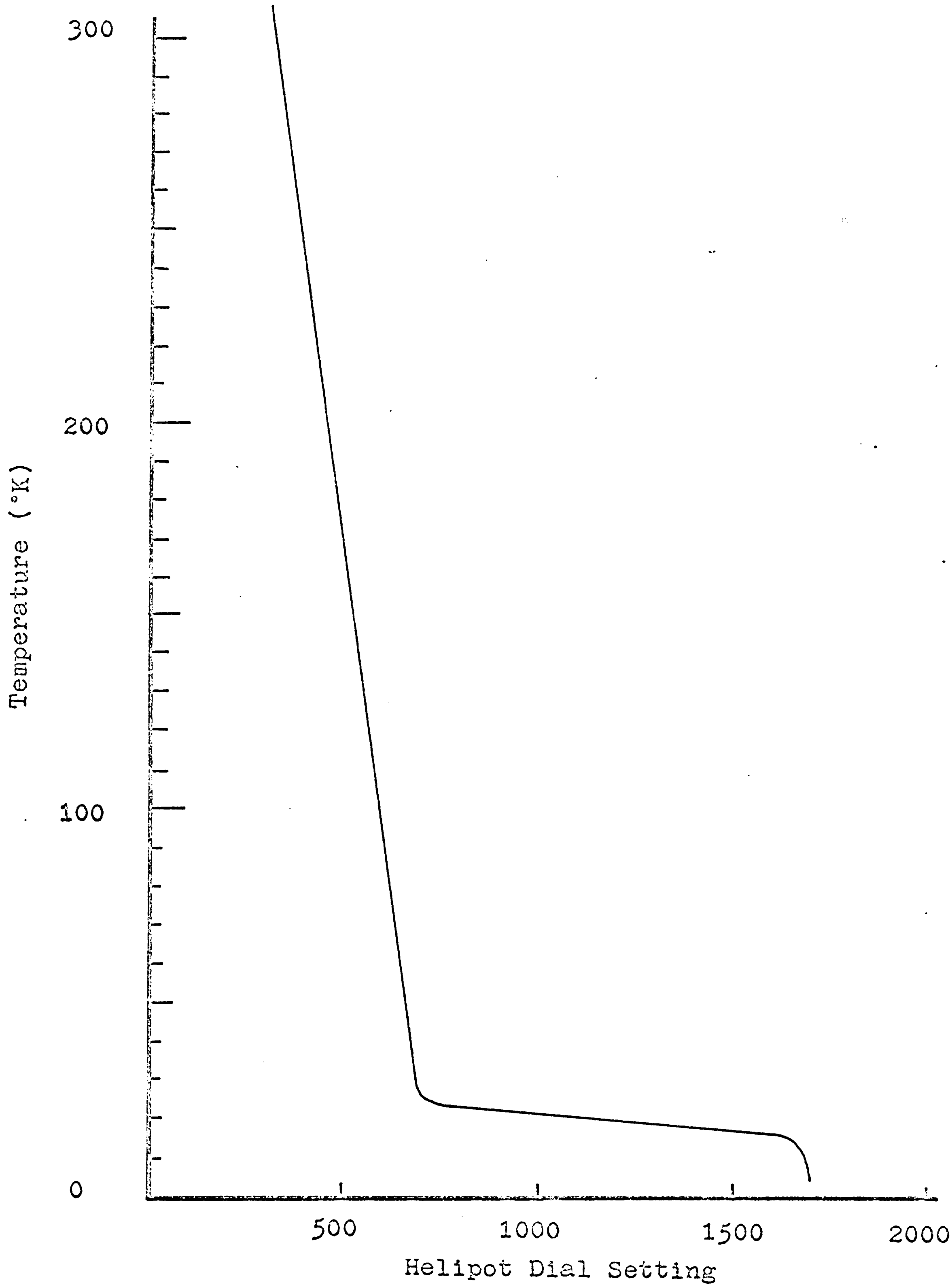

300
200
100
0
Temperature (°K)
500
1000
1500
2000
Helipot Dial Setting

Figure 5

cold trap. Pressure was monitored with a CVC thermocouple vacuum gauge for roughing out and a Phillips Gauge for measuring the ultimate pressure of the system -- about 5×10^{-5}mm. Operation of the Cryo-Tip required a small auxiliary pump in conjunction with clearing air from high pressure gas lines to prevent freezing at liquid nitrogen and liquid hydrogen temperatures.

It is interesting to note that the detector itself had a great deal to do with the ultimate pressure of the vacuum chamber. The vacuum pump and cold trap could only pull the system to 1×10^{-4}mm., but when liquid hydrogen began to form, the detector temperature would drop rapidly and act as a very efficient cold trap. The pressure would then drop to 5×10^{-5}mm. During some of the low temperature runs, the detector would give a very noisy spectrum, which suggests that undesirable material had been trapped on the surface of the detector. The Cryo-Tip has a dewar purge system which allows the vacuum to be broken with dry nitrogen. The detector then undergoes a rapid, frost-free warm-up. Subsequent cooling would always result in satisfactory detector operation at low temperatures.

Specific Procedure

The equipment was started several days before the first low temperature run and was never turned off, so the only drift encountered was long term drift. Arbitrary gain settings were used on the

A-61 main amplifier of the 256 Channel Analyzer since the energy versus channel number zero was not required. Before the first run the controls were adjusted to give a satisfactory spectrum; they were then locked for the duration of the temperature runs. Each day the supply voltages of the 256 Channel Analyzer were adjusted, if they had changed during the night, to the optimum settings learned from experience. After-cool down of the system was started, spectra were taken to qualitatively monitor the detector performance.

Low temperatures could be maintained only with high gas pressure, and it took most of the gas cyclinder pressure just to cool the system. Thus, cool-down was achieved as rapidly as possible and no attempts were made to stabilize the temperature for a spectrum until low temperatures were reached. The temperature was raised by increasing the back pressure at the hydrogen expansion valve. The limited lifetime of the gas cyclinders did not allow more than a few data points to be taken at any given temperature. To determine a data point, after achieving good temperature control at a desired temperature, a spectrum was taken with a given detector bias voltage. Each spectrum peak was straddled by test pulses from the double-height pulser. For each peak, the three channel numbers were manually read from the memory of the analyzer; the automatic print-out mechanism was not reliable. The temperature, test pulser supply voltage and attenuation factor, bias voltage setting, leakage current (if any), and peak channel numbers were then noted and recorded. The pulse rise time out of the preamplifier and main amplifier was also noted and photographed for the low temperature runs with the α source.

After it was determined that the rise time did not change with temperature, the pulse shape was monitored, but not photographed, for the β source.

DETERMINATION OF ϵ

Procedure

The detector heat sink was mounted on the Cryo-Tip "cold-finger" and placed in an evacuated chamber. There the detector was continually exposed to a radiation source. The detector was surrounded by a radiation shield, so the source could be "turned off" if desired.

When the system had achieved a desired steady-state temperature, the pulses out of the preamplifier were examined and photographed. For all temperatures, the pulses had a rise time of less than 50 nanoseconds. It was apparent that the pulse shape was determined by the time constants of the preamplifier (40 nanosecond rise time; 40 microsecond fall time) and not by the geometry and dielectric relaxation time of the detector.

A spectrum was then taken with the Analyzer with 100 seconds live counting time. The detector was then unplugged and the double height pulser used to bracket each spectrum peak. This process was repeated at least three times with three different bias voltages. Then the temperature of the system was changed and the whole process repeated. At times, difficulty was experienced with the Analyzer. The 256 Channel Analyzer is a small-scale vacuum-tube computer whose numerous sections interact in a complex and subtle manner. The automatic print-out mechanism turned out to be unreliable: it could not print out the same sequence of numbers twice without error.

The manual memory read-out mode was used to determine the spectrum peaks.

Data Analysis

The total energy of the incident ionizing particle is equal to the number of electron-hole pairs created times the average energy per charge pair, if the particle is stopped in the depleted region of the detector. Since the output of the preamplifier is proportional to the integral of the input current, the Analyzer is measuring relative charge per channel:

$$\epsilon_{apparent} = E_T/N$$
$$= E_T/Q_c/q$$

where

E_T = total energy of incident radiation

N = number of collected charge pairs

Q_c = charge collected

q = charge per pair

By assuming the Analyzer is linear between the upper and lower test pulser peaks, the charge producing the spectrum peak is readily determined:

Let C_l = channel no. of lower pulser peak

C_u = channel no. of upper pulser peak

C_s = channel no. of source peak

and

Q_l = charge producing peak in channel C_l

Q_u = charge producing peak in channel C_u

Q_c = charge producing peak in channel C_s

Then

$$Q = \lambda C + b \quad \text{(by assumption)}$$

Given: (Q_1, C_1), (Q_u, C_u), and C_s

Find: Q_c

$$\lambda = \left(\frac{Q_u - Q_1}{C_u - C_1}\right), \quad b = Q_u - \left(\frac{Q_u - Q_1}{C_u - C_1}\right)C_u = \left(\frac{Q_1 C_u - Q_u C_1}{C_u - C_1}\right)$$

Thus

$$Q_c = \left(\frac{Q_u - Q_1}{C_u - C_1}\right) C_s + \left(\frac{Q_1 C_u - Q_u C_1}{C_u - C_1}\right)$$

$$= \frac{Q_u(C_s - C_1) + Q_1(C_u - C_s)}{C_u - C_1}$$

The pulser peaks are related through the voltage divider networks into which the capacitors dump their charge. These networks were measured and calculated to have a ratio of = 1.1466. Hence Q_u/Q_1 = 1.1466. To accurately determine Q_u, corrections must be made for factors such as cable loss, network time constant interactions, decay of the charging capcitor charge during switching, and the non-idealness of the step function that the test pulser approximates. Analysis of these factors was carried out by Emery [6]. The results are presented here only as a numerical correction factor.

$Q_L = \alpha \cdot C_T V_o L$ where α = correction factor

C_T = test capacitance (1.1372 pf)

V_o = source voltage of pulser

L = voltage attenuator setting

Hence

$$\epsilon_{apparent} = \frac{E_T q \, (C_u - C_1)}{Q_u(C_s - C_1) + Q_1(C_u - C_s)}$$

and

$$= \frac{E_T q}{Q_1} \; \frac{1}{1 + .1466 \, \frac{(C_s - C_1)}{(C_u - C_1)}}$$

$$= \frac{E_T q}{\alpha C_T V_o L} \; \frac{1}{1 + .1466 \, \frac{(C_s - C_1)}{(C_u - C_1)}}$$

$$= \frac{3.376931}{V_o L} \; \frac{E_T}{1 + .1466 \, \frac{(C_s - C_1)}{(C_u - C_1)}}$$

Recall that the value of $\epsilon_{apparent}$ is a function of bias voltage, charge collection efficiency, and the effects of trapping and recombination. But trapping and recombination are related to the charge collection efficiency, and the charge collection efficiency is a simple function of the bias voltage for high voltages. The charge collection efficiency has been defined as

$$\eta = Q_c/Q_g \qquad \text{where } Q_g = \text{generated charge.}$$

It may be shown [6] that the charge collection efficiency is

$$\eta = \frac{\mu\tau E}{w} (1 - e^{-w/\mu\tau E})$$

$$= \frac{1}{\gamma}(1 - e^{-\gamma})$$

where

μ = carrier mobilities

τ = carrier lifetimes

E = detector electric field

w = parallel electrode spacing

If γ is sufficiently small, we may use a high field approximation and expand:

$$\eta = \frac{1}{\gamma} [1 - (1 - \gamma + \frac{\gamma^2}{2} - \frac{\gamma^3}{6} + \ldots + (-1)^n \frac{\gamma^n}{n!})]$$

$$= 1 - \frac{\gamma}{2} + \frac{\gamma^2}{6} + \ldots + (-1)^{n+1} \frac{\gamma^{n-1}}{n!}$$

For γ small,

$$\eta \cong \frac{1}{1 + \frac{w}{2\mu\tau E}}$$

$$\cong \frac{1}{1 + \frac{\text{constant}}{V_D + V_o}}$$

where

V_D = detector bias voltage

V_o = diode contact potential

For the large bias voltages used, $V_o \gg V_o \simeq .5$ volt. Hence, the charge collection efficiency approaches unity as the bias voltage becomes infinite.

$$Q_c = \eta Q_g$$

and

$$\epsilon_{apparent} = \frac{q\ E_T}{Q_c}$$

$$= \frac{q\, E_T}{\eta\, Q_g}$$

$$= \varepsilon_\infty \left(1 + \frac{\text{constant}}{V_D + V_o}\right)$$

By plotting $\varepsilon_{apparent}$ versus $1/(V_D + V_o)$, we may extrapolate to infinite bias to determine ε_∞. A least-squares-fit was used to determine the vertical intercept of $\varepsilon_{apparent}$ versus $1/(V_D + V_o)$. The results of one low temperature data run are shown in Figure 6.

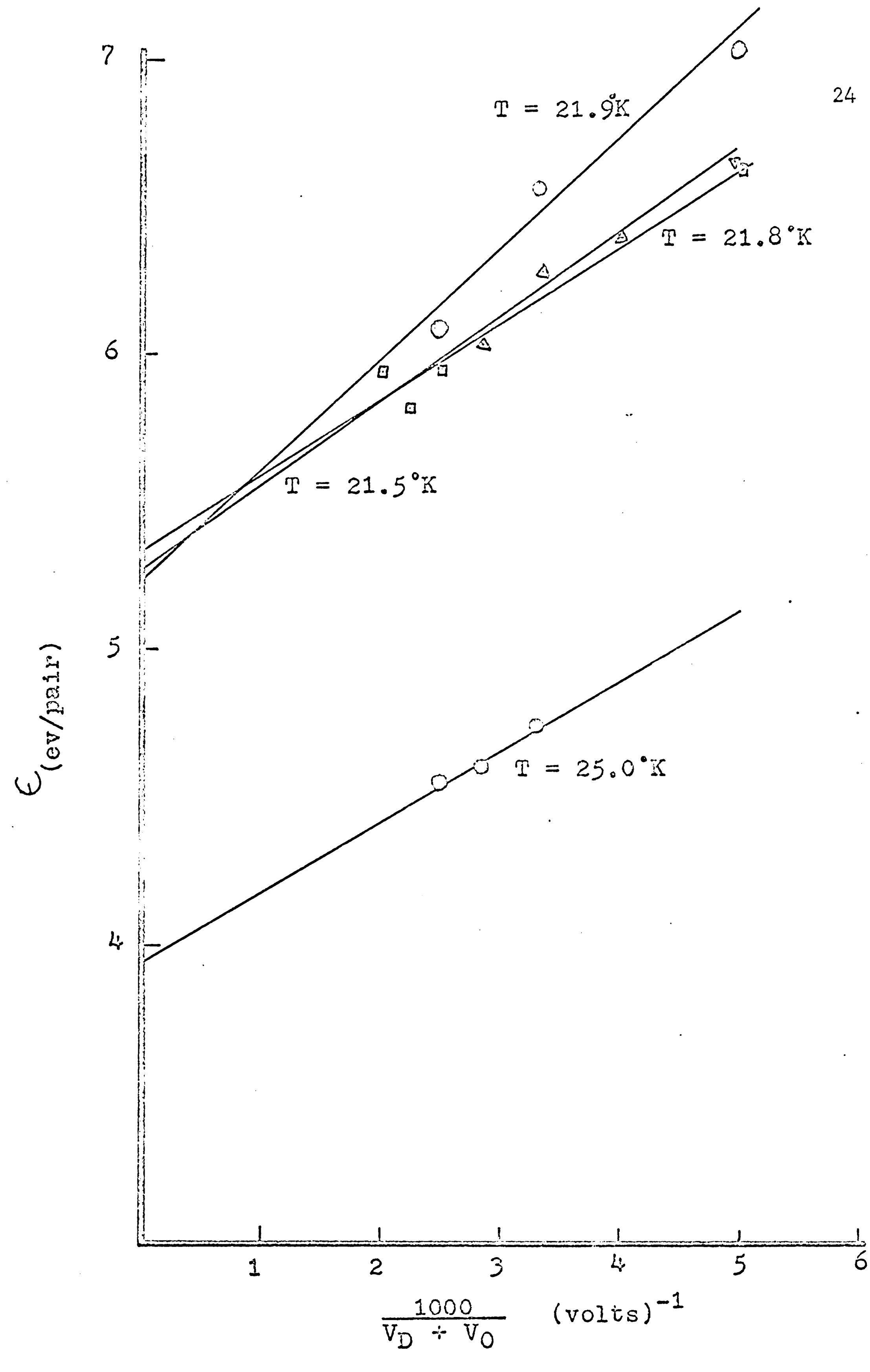

7
6
5
4
T = 21.9°K
T = 21.8°K
T = 21.5°K
T = 25.0°K
$\epsilon_{(ev/pair)}$
1
2
3
4
5
6
$\frac{1000}{V_D + V_O}$ (volts)$^{-1}$

Figure 6

RESULTS

The quantitative results of this thesis are best shown in pictorial and graphical form. Figure 6 shows a plot of $\epsilon_{apparent}$ versus inverse detector voltage. A computer program was written and used to determine each point.

It was assumed that the uncertainty in the ϵ determination process was independent of temperature. This assumption was made of necessity; at low temperatures, there was insufficient running time to take more than a few points at a given temperature. Repeated measurements of ϵ at room temperature showed an uncertainty of $\pm$ 0.035 e.v. The uncertainty in temperature is equal to the calibration accuracy of the thermometer -- $\pm$ 1°K. A small temperature change always resulted in a noisy spectrum, and the results were judged unacceptable.

A Plot of relative pulse height versus temperature is shown in Figure 7. The effect of increasing bias voltage on the charge collection efficiency is evident.

Representative spectra are indicated in Figure 8. The downward shift of the spectrum peaks corresponds to the decrease of pulse height with temperature.

The qualitative results of this thesis are of equal importance. This thesis shows that the different results of Emery [8] and Dodge [4,5] cannot be resolved with arguments concerning dielectric relaxation effects in silicon detectors.

This thesis indicates that more extensive measurements must be made over a wider temperature range with various detectors to see if the data of Dodge and Emery are really representative of silicon detectors in general; it may be that the lack of control over certain steps in the process of detector manufacture causes individual detectors to have a characteristic pulse height spectrum. If this is the case, then each detector must be individually calibrated and the concept of ϵ would lose its usefulness. One of the great advantages of semiconductor radiation detectors is the linear response over wide energy ranges. If measurements show that ϵ is relatively constant, or even a characteristic function of temperature, for a given type of detector, then the utility of these detectors would be greatly enhanced, since extensive calibration of individual detectors would not be necessary.

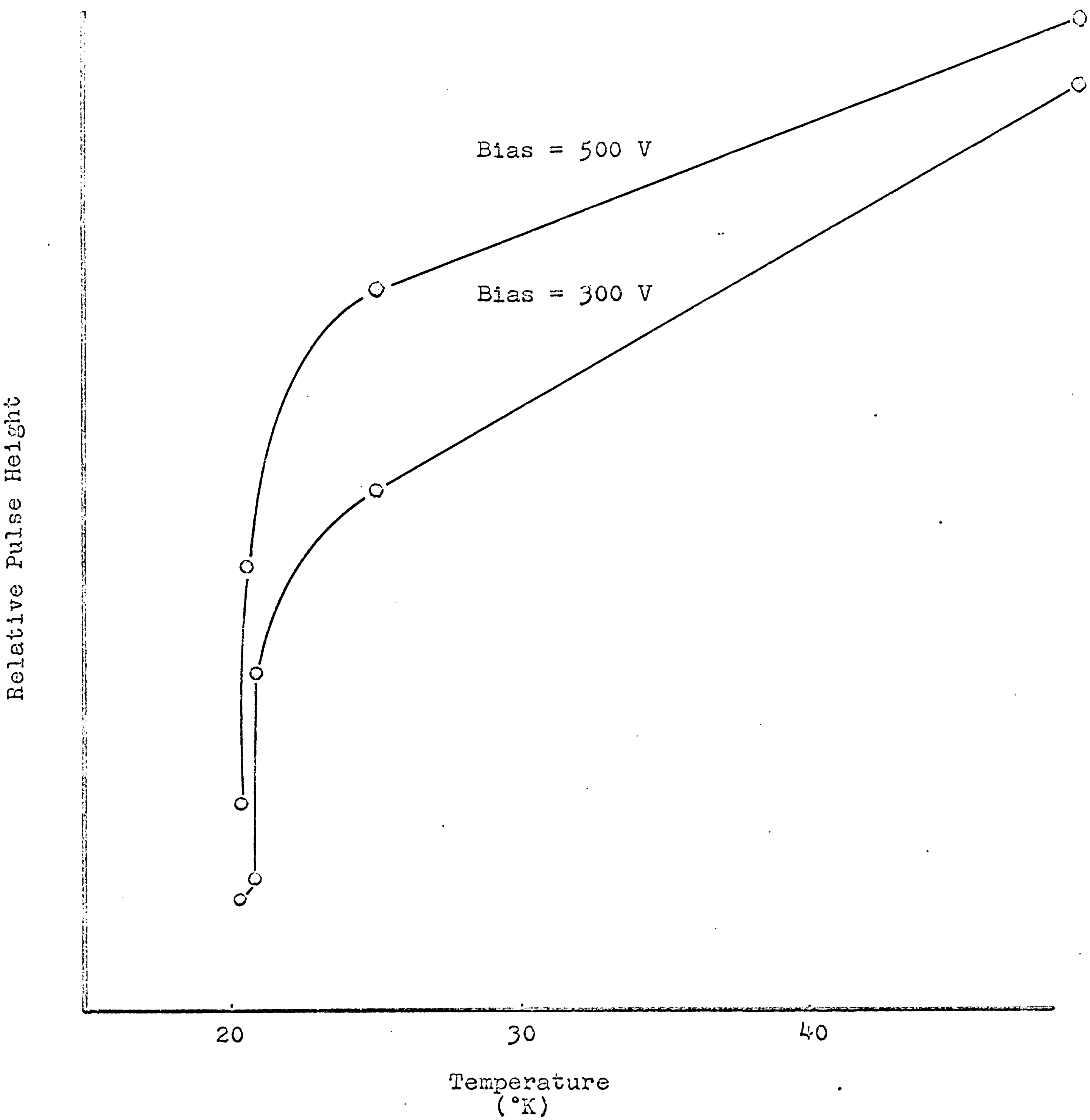

Bias = 500 V
Bias = 300 V
Relative Pulse Height
20
30
40
Temperature
(°K)

Figure 7

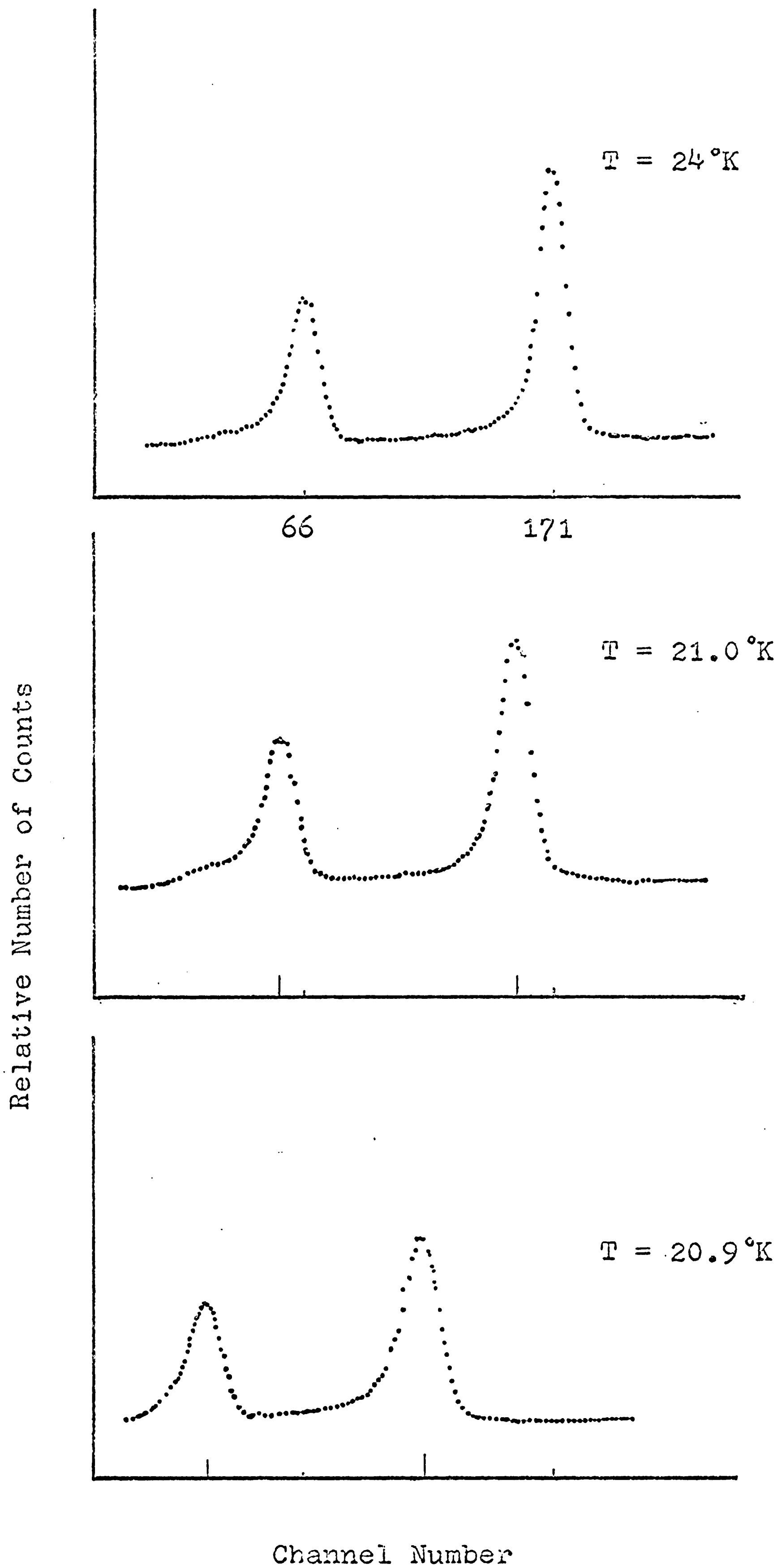

T = 24°K
66
171
T = 21.0°K
T = 20.9°K
Relative Number of Counts
Channel Number

Figure 8

CONCLUSIONS

The detector pulse spectrum was monitored as the system was cooling down. The pulse height was not observed to change to any great degree, so it was assumed that ϵ is relatively constant down to 25°K. The limited available operating time with the gas supply made it desirable to take data at the lower limits of the refrigerator, since the large changes in pulse height were observed there.

Careful examination of the pulse photographs showed that the rise time was constant; it was not a function of the detector temperature. The pulse height was observed to change with the detector temperature; hence it must be concluded that dielectric relaxation effects are not responsible for the anomaly in ϵ, and that ϵ apparently undergoes a large, sudden change in the temperature region between 20-25°K. Spectra and pulse shapes were examined as the temperature was alternately increased and decreased. The swift and dramatic change in pulse height did not depend on the rate of temperature change or the direction of the temperature change.

It is evident that the behavior of ϵ becomes quite interesting just at the lower limit of the temperature measurements that were made. Further measurements have been planned. With suitable pumping on the exhaust line to the hydrogen exhaust valve, it is possible to extend the temperature measurements to 15°K. A high pressure gas supply has been designed which will allow stable operation of the

Cryo-Tip for long periods of time.

The process which involves the greatest experimental error and consumes the greatest time in the data-taking process is the spectrum read-out from the 256 channel pulse height analyzer. A faster, more accurate method of read-out is anticipated.

Further measurements are planned for different radiation sources. In addition, non-lithium compensated silicon surface barrier detectors will be used for comparative measurements. Attempts will be made to determine the depletion depth of a detector as a function of bias voltage and temperature.

BIBLIOGRAPHY

1. Air Products and Chemicals, Inc., Allentown, Pennsylvania.

2. L. E. Barton, "Measuring Temperature", Electronics,38, May 4 (1962).

3. G. Dearnaley and D. Northrop, Semiconductor Counters for Nuclear Radiations, Wiley, Second Edition (1966).

4. W. R. Dodge, S. R. Domen, A. T. Hirshfeld, and D. D. Hoppes, "The Anomaly in the Response of Semiconductor Detectors at Low Temperatures", IEEE Transactions on Nuclear Science, NS-11, No. 3, 238, June (1964).

5. W. R. Dodge, S. R. Domen, T. F. Leedy, and D. M. Scopik, "Measurement of the Mean Energy Required to Create an Electron-Hole Pair in Silicon Between 6° and 77°K", Physical Review Letters, 17, No. 12, 653, Sept. 19 (1966).

6. F. E. Emery, "The Average Energy Expended Per Ionized Electron-Hole Pair in Semiconductors", Ph.D. Thesis, Rice University, Houston, Texas (May 1965).

7. F. E. Emery and T. A. Rabson, "On the Accuracy of the Calibration Techniques Used with Semiconductor Detectors", Nuclear Instruments and Methods, 34, 1, 171 (1965).

8. F. E. Emery and T. A. Rabson, "Temperature Dependence of Average Energy Per Pair in Semiconductor Detectors", IEEE Transactions on Nuclear Science, 1, NS-13, No. 1, 48, Feb. (1966).

9. Oak Ridge Technical Enterprises Corporation, Oak Ridge, Tennessee.

10. J. H. Simpson, "Theory of the Temperature Coefficient of the Forward Voltage of a P-N Junction", Solid State Technology, 22, September (1964).

11. D. Strominger, J. M. Hollander and G. T. Seaborg, "Table of Isotopes", Rev. Mod. Phys., 30, #2 (1958).

12. Tennelec, Oak Ridge, Tennessee.

ACKNOWLEDGMENTS

I would like to express my thanks to those who helped me on this project. In particular, the following individuals deserve special recognition:

My thesis advisor, Dr. T. A. Rabson, whose suggestions, guidance, and funds made this project possible.

Bill Peters, Chief Electronics Technician, who steered me clear of many experimental pitfalls and helped me keep the equipment functioning properly.

Dr. H. C. Bourne, Chairman of Electrical Engineering, who was responsible for providing my N.S.F. financial support during this period; the United States Atomic Energy Commission who funded the project.

My wife, Ann, for her patience and constant encouragement.