# THE PREPARATION AND OPERATION OF LITHIUM DRIFT GERMANIUM DETECTORS

by

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## ABSTRACT

Lithium drifted germanium detectors have been prepared for use as high resolution gamma ray spectrometers. The fabrication procedure and the problems which can arise during preparation are discussed in detail. Using the techniques described, germanium detectors having the following characteristics were prepared.

| Active | Volume          | Total | Resdlu | ition | at | 661 | keV |
|--------|-----------------|-------|--------|-------|----|-----|-----|
| 1.0    | $cm^3$          |       | 5.0    | KeV   |    |     |     |
| 0.5    | cm <sup>3</sup> |       | 4.0    | KeV   |    |     |     |
| 2.0    | $cm^3$          |       | 4.0    | KeV   |    |     |     |
| 1.7    | cm <sup>3</sup> |       | 2.9    | KeV   |    |     |     |

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### CHAPTER 1

#### INTRODUCTION

It is frequently important to measure gamma ray energies with high accuracy and with good efficiency in many fields of nuclear physics. Lithium drift semiconductor detectors have recently made it possible to measure gamma ray energies with high resolution simultaneously over a wide range of energy. Previously, it was necessary to use a very low efficiency magnetic spectrometer if high energy resolution was desired or to use a moderate resolution (>8%) NaI scintillation detector if good efficiency was necessary. Lithium drift germanium detectors combine a resolution close to that of magnetic spectrometers with the high efficiency and wide energy range characteristic of NaI scintillation detectors. Currently the detection efficiency of germanium detectors is about ten times less than scintillation detectors but this defect will be overcome as the active volume of germanium detectors is increased.

With germanium detectors it is possible to do a great range of experiments which were not feasible before because of limitations in the resolution or efficiency of previous detectors. In addition, many previous experiments can be redone with an order of magnitude increase in accuracy. Two fields which have benefitted particularly by the use of germanium detectors are lifetime measurements of excited nuclear states (Alexander and Allen 1965; Alexander, Litherland, and Broude 1965) and the precise analysis of X-Rays from mu-mesic atoms (Bardin et al. 1966a, Bardin et al.

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1966b). Direct gamma ray spectra measurements (Freedman, Wagner, Porter, and Bolotin 1966), neutron activation analysis (Hughes, Kennett, Prestwich, and Wall 1966), and gamma ray coincidence studies will all be made more accurate using germanium detectors.

This thesis presents the work done at the University of British Columbia on the preparation of lithium drift germanium detectors. In Chapter 2, the theory of the operation of lithium drift detectors is presented and in Chapter 3 the apparatus which was built to fabricate detectors is given. In Chapter 4 the fabrication procedure is given and in Chapter 5 the experimental results are presented. Finally, in Chapter 6 some conclusions are drawn on the preparation and operation of lithium drift detectors.

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#### CHAPTER 2

#### THEORY OF DETECTOR OPERATION

## A. Interaction of Gamma Rays with a Semiconductor Crystal

The detection of gamma rays with semiconductor detectors is based on the interaction of gamma rays with the electrons in a semiconductor crystal. Detection of a gamma ray can be considered as proceeding in two steps. First, the gamma ray interacts directly with one of the electrons. The resulting energetic electrons then interact with the other electrons in the crystal producing many free electrons in the conduction band and holes in valence band. The electrons and holes are collected and their total charge measured to give the energy of the incoming gamma ray.

#### i) Interaction with Crystal Electrons

There are three ways in which an incoming gamma ray can lose energy to the electrons in a crystal. The first is photoelectric absorption in which all the gamma ray energy is used to excite an electron from an atom in the crystal. The kinetic energy of the electron,  $E_{\rm e}$ , is then:

$$E_{e} = E_{\gamma} - E_{b}$$
(2-1)

where:

 $E_{i}$  = energy of the gamma ray

Momentum is conserved by the recoil of the residual ion. The probability for photoelectric absorption is therefore largest for K shell electrons which are most strongly coupled to the nucleus. The photoelectric absorption cross section for K shell electrons was given by Hall (1936) as:

$$\sigma_{\rm p} = \frac{4\sqrt{2}}{137} \left\{ \frac{m_{\rm o}c^2}{hv} \right\}^{\frac{7}{2}} \phi_{\rm o}$$
(2-2)

assuming:  

$$hv < (non-relativistic)  
 $hv >>$ binding energy of K shell electron  
where:  
 $\sigma_p = K$  shell photoelectric absorption cross section  
 $Z =$  atomic number of atom  
 $m_o =$  mass of electron  
 $hv =$  energy of incoming gamma ray  
 $\phi_a =$  constant = 6.6 x  $10^{-25}$  cm<sup>2</sup>$$

for germanium:

$$\sigma_{\rm p} = \frac{3.37 \times 10^{-27}}{(\rm hv)^{7/2}} ~\rm cm^2$$
 (2-3)

where hulls given in MeV.

This process is dominant for low energy gamma rays (less than 200 KeV) in germanium detectors.

The second way an electron may receive energy from a gamma ray is by Compton scattering. The process can be considered as an elastic collision between the gamma ray and an electron in which the energy is shared and the the energy of the emergent photon is less than that of the incident photon.



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The energy of the incoming gamma ray is so large compared to the binding energy of the crystal electrons that the electrons behave as if they were unbound. The energy of the scattered gamma ray is given by:

$$h\upsilon' = \frac{h\upsilon}{1 + \frac{h\upsilon}{mc^2} \left[1 - \cos\theta\right]}$$

The cross section for Compton scattering was given by Klein and Nishina (1929) as:

$$\sigma_{c} = 2\pi r^{2} \left[ \frac{1+\alpha}{\alpha^{3}} \left\{ \frac{2\alpha(1+\alpha)}{1+2\alpha} - \log(1+2\alpha) \right\} \right]$$
(2-5)

+ 
$$\frac{1}{2\alpha} \log(1+2\alpha) - \frac{1+3\alpha}{(1+2\alpha)^2}$$

where:

$$r_{0} = \text{classical electron radius (2.818 x 10^{-13} \text{ cm})}$$
  

$$\alpha = \frac{h_{v}}{m_{c}c^{2}}$$
  

$$hv = \text{energy of incoming gamma ray}$$
  

$$m_{0} = \text{rest mass of electron}$$

Compton scattering is the dominant process in germanium detectors for gamma rays in the energy range 200 KeV to 6 MeV.

The third excitation process is pair production. In this process a gamma ray interacts with the Coulomb field of a nucleus and creates a positron-electron pair. In the center of mass coordinate frame the positron and electron conserve momentum by going off in opposite directions. Conservation of energy then requires that each has kinetic energy:

K.E. 
$$e^+ = \frac{h\nu}{2} - m_o c^2$$

(2-6)

-13:

The total pair production cross section,  $\sigma_p$ , was given by Bethe and Bacher (1936) as:

$$\sigma_{\rm p} = \sigma_{\rm o} Z^{5} \left| \frac{28}{9} \ln \left| \frac{2h}{m_{\rm o}c^2} \right| - \frac{218}{27} \right|$$
 (2-7)

where:

assuming:

 $\sigma_{o} = 5.80 \times 10^{-28} \text{ cm}^{2}$  Z = charge of nucleus  $m_{o} = \text{mass of electron}$   $m_{o}c^{2} << h v << 137 m_{o}c^{2} Z^{-1/3}$ 

The positron and electron are quickly slowed down by collisions with other electrons and the positron eventually annihilates with an electron in the crystal to produce two photons of energy  $m_0c^2$  (0.510 MeV). If one of the annihilation photons escapes from the crystal the total energy released in the crystal will be  $hv - m_0c^2$ .<sup>1</sup> This process thus yields a peak (called the single escape peak) in the detected energy spectrum 0.51 MeV below the full energy peak. Similarily, if both annihilation photons escape, the energy given to the crystal is  $h v - 2m_0c^2$  producing a double escape peak in the energy spectrum 1.02 MeV below the full energy peak. The pair production process is possible only for gamma rays above 1.02 MeV and is the dominant process above six MeV in germanium.

The variation of the theoretical absorption coefficients with gamma ray energy in germanium for photoelectric absorption, Compton scattering, and pair production is shown in Figure 2-1.

The three processes described for the interaction of a gamma ray



Figure 2-1 Variation of Theoretical Absorption Coefficients with Energy.

with the crystal electrons are not exclusive since the degraded photon from a Compton process or an annihilation photon can further interact by another Compton or photoelectric process. More of the gamma ray energy is given to the crystal electrons by these multiple processes and therefore the number of counts in the full energy peak is increased relative to the Compton background. The probability for occurrence of these multiple processes increases with crystal volume and therefore large detector volumes are very desirable.

#### ii) Conversion of Electron Energy to Ionized Charge

The energetic electrons produced by a gamma ray lose energy by inelastic collisions with the bound electrons.

The principal way free charges are produced is by the energetic electrons exciting electrons from the valence band to the conduction band. For every electron excited a hole is produced in the valence band and the energy lost is at least the band gap energy of 0.67 eV for germanium.

Another way the energetic electrons can lose energy is by interacting with the crystal lattice. The interaction excites the lattice into an optical mode of vibration with the energy exchange being quantized and characterized by the Raman frequency of the lattice (5 x  $10^{-3}$  eV for germanium).<sup>2</sup>

Thirdly, large numbers of very low energy electrons and holes remaining after the first two processes and not having sufficient energy to produce secondary ionization, lose their energy by thermal collisions with the lattice.

Goulding (1965b) gave a diagramatic representation of the energy

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loss process which is given in Figure 2-2.

B. Use of a Semiconductor Crystal as a Detector

A large number of electron-hole pairs are produced when a gamma ray interacts with a semiconductor crystal. If an electric field is applied to the crystal, the electrons and holes are separated and move to opposite electrodes. The charge which is collected in the external circuit will thus be proportional to the energy of the interacting gamma ray.



Unfortunately, in normal germanium or silicon single crystals it is very difficult to measure the charge flucuations due to gamma rays because the leakage current is very high. It would, therefore, be necessary to cool the crystal to very low temperatures where the impurity carriers become inactive and the leakage current low in order to use normal germanium as a detector.  $^{3}$ 

Another way to reduce the leakage current is to use a reverse biased n-p junction. The carrier depleted region at the junction could then be used as a detector. This type of detector (usually silicon) is widely used

3. Such operation has, in fact, been employed. The resolution obtained, however, was not as good as that possible by the following technique.

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These now become parents for future generation if their energy is adequate for production of secondaries

e<sub>r</sub> = Raman phonon energy for lattice e<sub>g</sub> = Band gap of material p = Assumes a random value in the range 0 to 1

Figure 2-2 The Energy Loss Process

for the detection of charged particles but, because of its small active volume, it is not normally used for gamma rays. Before the development of lithium drift detectors, however, Donovan, Miller, and Foreman (1960) used a high resistivity diffused junction counter for the detection of 120 KeV gamma rays.

Lithium drifted detectors also use a reverse biased junction but in between the p and n regions is an impurity compensated region.



The impurity compensated region can be very large. Early lithium drift detectors were small silicon devices which gave a full energy peak intensity which was only one per cent of the Compton edge intensity for 662 Kev gamma rays (Mayer, Bailey, and Dunlap 1960). Germanium is preferable to silicon because of its greater atomic number and therefore larger cross section for gamma rays. Freck and Wakefield (1962) reported operation of a germanium detector 1.5 mm deep at a bias of 12 volts. Since then many groups have progressively enlarged the active volume of detectors. Malm and Fowler (1966) have recently reported operation of a germanium lithium drift coaxial detector with an active volume of 54 cm<sup>3</sup> at 600 volts bias.

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# C. Necessary Properties of Germanium for Detectors

To make good detectors the germanium crystal used must have very high purity and few crystal faults because a long carrier lifetime is desired and good compensation of impurities by lithium is necessary.

The carrier lifetime should be long because it is desired to have most of the charge produced by the gamma ray collected by the applied electric field and supplied to the amplifier rather than lost by recombination processes within the crystal. Traps provide intermediate levels in the energy band gap through which recombination and generation processes can take place. Traps are due to impurity centers or crystal imperfections (vacancies, dislocations, etc.) and may exhibit preferential trapping properties for either electrons or holes thus inhibiting collection of carriers in the detector. Goulding (1965c) gives a discussion of the effects and causes of traps. He points out that heat treatments increase the number of traps and therefore should be kept to a minimum.

Very high purity germanium is necessary because impurities like oxygen can form complex ions with lithium (like LiO<sup>+</sup>) which are less mobile than the Li<sup>+</sup> ion. Oxygen concentrations greater than one part in 10<sup>9</sup> greatly reduce the drift rate of lithium (Goulding 1965d). Lithium can also precipitate and lose its electrical activity if vacancies are present in the crystal. The quality of the initial germanium crystal, therefore, determines to a great extent the quality of the resulting detector.

In order for sufficiently low leakage currents to be realized, the conductivity of the material must be governed by the density of thermally excited carriers rather than by impurity atoms. In other words, the conductivity must be intrinsic and not extrinsic at the operating temperature. In intrinsic material the thermally generated current density,  $J_i$ , is given by:

$$J_{i} = q \cdot n_{i} \cdot E \cdot (\mu_{h} + \mu_{e})$$
(2-8)

where:  $q = charge per electron (1.6 \times 10^{-19} coul)$   $n_i = intrinsic carrier concentration$  E = electric field  $\mu_h = hole mobility$  $\mu_e = electron mobility$ 

the dependence of  $n_i$ ,  $\mu_h$ , and  $\mu_e$  on temperature, T,was given by Conwell (1958) as:

$$n_i(T) \approx 1.76 \times 10^{16} \cdot T^{3/2} \cdot e^{-4550/T} \text{ cm}^{-3}$$
 (2-9)

$$\mu_h(T) \simeq 1.05 \times 10^9 \cdot T^{-2.33} \text{ cm}^2/\text{volt-sec}$$
 (2-10)

$$\mu_{e}(T) \simeq 4.9 \times 10^{7} \cdot T^{-1.66} \text{ cm}^{2}/\text{volt-sec}$$
 (2-11)

where:  $T = absolute temperature (^{O}K)$ The dependence of n<sub>i</sub> on temperature is shown in Fiqure 2-3 and the dependence of  $\mu_{\rm b}$  and  $\mu_{\rm e}$  on temperature is shown in Fiqure 2-4.

It is necessary to operate germanium detectors at liquid nitrogen temperature  $(77^{\circ}K)$  to keep the thermal generation current very low and thus contribute very little to the total noise. At  $77^{\circ}K$  the intrinsic carrier density given by equation (2-9) is:

$$n_i(77) \simeq 2.5 \times 10^{-7} \text{ cm}^{-3}$$

However, the highest purity germanium obtainable commercially has about





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 $10^{13}$  impurities per cm<sup>3</sup> of all one type (acceptor or donor). At 77<sup>o</sup>K most of the impurities will be ionized and therefore the carrier density due to impurities,  $n_{imp}$ , will be:

$$n_{imp}(77) \simeq 10^{13} \text{ cm}^{-3}$$

There is a very great difference between  $n_i(77)$  and  $n_{imp}(77)$ . To reduce  $n_{imp}(77)$  compensation of the impurities in the crystal is done by introducing impurities of the opposite type into the crystal. If there is an exact balance of acceptor and donor impurities then the carrier concentration will be the intrinsic carrier concentration and the conductivity will be intrinsic.

The electron and hole mobilities, however, will not be the same as the intrinsic material since they are decreased by scattering of carriers from the charged impurities (Adler, Smith, and Longini 1964). Since the mobilities are decreased the charge collection time will be increased by impurity scattering. If the acceptor and donor impurities are paired impurity scattering is reduced. This ion pairing can be done with lithium ions by doing final compensation at a lower temperature where the Li<sup>+</sup> ion is just mobile enough to be attracted by the acceptor impurity but not mobile enough to move very far by drifting.

#### D. Lithium Ion Drifting

To reduce the number of ionized impurities in germanium the technique of lithium ion drift has been developed. A germanium crystal is refined so that the major impurity is the acceptor gallium. Lithium, which is a donor impurity, is used to compensate the gallium impurity and thus reduce the net impurity ion concentration. Lithium is used because it is a very mobile donor impurity with a low ionization energy (0.0093 eV) in germanium.

The lithium is usually vacuum evaporated onto one face of the crystal which is then heated to 450<sup>°</sup>C for five minutes to allow the lithium to diffuse into the crystal. The diffusion of impurities into semiconductors is discussed very completely by Warner and Fordemwalt (1965). After diffusion the lithium concentration has the distribution shown in Figure 2-5 and the concentration is given by:

$$N_d = N_0 \cdot \operatorname{erfc} \left| \frac{x}{2\sqrt{D_0 t}} \right|$$
 (2-12)

where:

N<sub>d</sub> = donor concentration at depth x from surface N<sub>o</sub> = lithium surface concentration t = duration of diffusion D<sub>o</sub> = diffusion constant

Since the germanium crystal is slightly p-type and a n-type lithium layer has been formed on one surface, there is a p-n junction at  $x_0$  where:

$$N_d = N_a$$
  
 $N_a = acceptor concentration in crystal$ 

and  $x_0$  is therefore obtained from:

$$N_{a} = N_{o} \cdot \operatorname{erfc} \left| \frac{x_{o}}{2\sqrt{D_{o}t_{o}}} \right|$$
(2-13)

When this p-n junction is reverse biased the positively charged lithium ions move into the p side of the junction where they compensate the negatively charged acceptor ions by charge neutralization. Fiqure 2-6 shows the growth of the compensated region after a short period of drifting.



Figure 2-5 Impurity Concentration versus Distance from Surface





Figure 2-6 Growth of the Compensated Region

The compensation is very exact since, for example, if a pile up of donors occurs in the compensated region the electric field gradient is modified so as to dissipate the excess concentration. Figure 2-7 shows the normal electric field distribution and that resulting from an excess of ions.

Following the arguments of Goulding (1965e) the rate of growth of the compensated (intrinsic) region can be estimated assuming that the current of lithium ions is due entirely to the electric field, that the diffusion current is negligible, and that the lithium ions have already drifted a distance W. In the intrinsic region  $N_a = N_d$  and the electric field is V/W where V is the applied voltage. The current of lithium ions per square cm,  $J_r$ , is then given by:

$$J_{L} = \mu_{L} \cdot N_{a} \cdot \frac{V}{W}$$
(2-14)

where:

 $\mu_L$  = mobility of lithium ions in the semiconductor at the drift temperature

The number of acceptors per unit area which can be compensated in time dt is therefore  $J_L$  dt and, since the acceptor concentration in the compensated material is  $N_a$ , the increase,  $\Delta W$ , in the thickness W of the intrinsic layer in time dt is given by:

$$N_{a} \cdot dW = \frac{V}{W} \cdot \mu_{L} \cdot N_{a} \cdot dt \qquad (2-15)$$

The drift rate,  $\frac{dW}{dt}$ , is:

 $\frac{\mathrm{d}W}{\mathrm{d}t} = \frac{V}{W} \cdot \mu_{\mathrm{L}} \tag{2-16}$ 







Figure 2-7 Normal Electric Field Distribution

Therefore by integration:

$$W^{2} = 2 \quad V \cdot \mu_{L} \cdot t$$

$$W = \sqrt{2\mu_{L} \cdot V \cdot t} \qquad (2-17)$$

Note that the drift rate is independent of the resistivity of the starting material but that it is increased by raising the temperature (since the Li ion mobility increases with temperature) or by increasing the applied voltage. The applied voltage is limited by surface breakdown and is typically 100 to 600 volts. The drift temperature has an upper limit above which the material becomes intrinsic and the crystal ceases to behave as a diode. Drift temperatures well below the intrinsic temperature are preferred to avoid compensation by the lithium of the thermally generated carriers. This overcompensation can be reduced by drifting at lower temperatures at the end of the primary drift. The thickness of the drifted region versus drift time for various drift temperatures is shown in Figure 2-8.

#### E. Surface Problems

The surfaces of the crystal containing the exposed junction are critical regions during drift. Problems can develop at this stage which can seriously affect the characteristics of the final detector.

Before drifting the edges are etched to remove the surface and expose a clean surface. Prior to etching the crystal faces are taped with an etch resistant tape to prevent etching of the lithium layer.<sup>4</sup> During drifting the crystal is kept in a dry inert atmosphere to reduce the collection

-15-



:

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80

100 I

200

300

÷

400

600



20

30

DRIFT TIME (hours)

40 50 60

7 8 9 10

4 5 6

60°C 50°C

40°C 300

2000

(mm)

DRIFTED DEPTH

4

3

2

ģ

87

2 -

1 .

1

2

3

of impurities on the junction. If impurities, such as water, do collect they can alter the electrical properties sufficiently such that the junction can be shorted and stop the lithium drifting. Under such conditions the impurities can be removed by re-etching the edges after which drifting will normally resume.

Sometimes the crystal stops drifting and cannot be re-started by edge etching. Staining the edges by reverse biasing in a copper sulphate solution to reveal the junction will then often show that somewhere the junction curves abruptly (usually at a corner).



This indicates that the junction has hit a bad spot in the crystal. After the bad spot has been sawn off and the edges re-etched drifting can often be resumed.

When drifting is completed and the crystal is ready for mounting, the junction surface condition is still very important because a stable, low conductance surface is needed to keep the total leakage current low. The surface states which are formed can have a profound influence on the final characteristics of the device. For a p-n junction the surface states can result in an inversion layer extending across the junction. The result of this is to greatly increase the junction area and therefore the capacitance

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and reverse leakage current increase.

Armantrout (1966) has studied the effect of surface states on lithium drift germanium detectors. The surface states sensitive to ambient conditions are present in or on the outside of the oxide layer which forms on the germanium when it is exposed to the atmosphere. The effect of these states is to alter the energy band structure of the crystal by introducing energy levels in the surface layer. For example, oxygen may gain a negative charge and behave as an acceptor site. To satisfy charge neutrality a hole is formed in the germanium near the surface thus creating a p-type inversion layer. Similarly, other absorbed atoms can result in a n-type or p-type inversion layer.

Llacer (1964) has proposed a model which provides a good explanation of the role of surface states in determining the leakage and voltage breakdown characteristics of a lithium drift detector. He suggests that the surface states may cause an inversion layer which extends across the intrinsic region and overlaps the opposite junction.



High fields are present where the inversion layer overlaps the opposite junction. Zener breakdown can occur at low bias and then the surface becomes a conducting channel resulting in high leakage current. The surface breakdown may occur initially as large pulses which are similar

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to pulses from radiation. It is, therefore, desirable to have as light an inversion layer on the surface as possible since the heavier the inversion layer the longer the surface channels.

Llacer (1966) has pointed out that if detectors could be constructed with high electric fields normal to the junction at the i-p junction then the resistance of the surface channel would be increased. At present, however, the best surface treatment found is a methyl alcohol rinse after a short etch. The detector is then immediately put in a good vacuum to maintain the condition of the surface.

#### F. Resolution of Germanium Detectors

The resolution of lithium drift germanium detectors is an order of magnitude better than that of NaI scintillation detectors. In fact, the overall resolution is limited not only by the quality of the detector but also by the noise and stability characteristics of the electronic equipment.

The ultimate resolution of germanium detectors can be estimated by considering the charge production processes which occur. If all the energy lost by a gamma ray in a detector was converted into ionization the signals produced by monochromatic radiation would show neglible flucuation. However, if the energy was dissipated by thermal processes then normal statisical fluctuations in the number of electron-hole pairs produced would be expected. In this case, the RMS fluctuation, <n>, of the number of pairs would be given by:

$$\langle n \rangle = \frac{E}{\varepsilon}$$
 (2-18)

where:

E = energy lost in the detector by the gamma ray

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- ε = average energy required to produce an electron-hole pair
  - = 2.94 eV per pair for germanium

The RMS fluctuation in energy,  $\Delta E_{rms}$ , would be:

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$$\Delta E_{\rm rms} = \langle n \rangle \cdot \epsilon = \sqrt{\epsilon E}$$
 (2-19)

The actual statisical fluctuation in germanium detectors is between those characterizing pure ionization and normal statisical fluctuation. Fano (1941) introduced the Fano factor as a convenient way of expressing this situation. It is defined as:

$$F = \frac{n_0^2}{n^2}$$
(2-20)

where:

 $n_{o}$  = observed RMS fluctuation

n = normal statisical fluctuation

The full width at half maximum,  $\Delta E_{FWHM}$ , of an energy peak is the convenient measure of resolution for gamma ray spectra. The  $\Delta E_{FWHM}$  for a Gaussian distribution is related to the RMS fluctuation by:

$$E_{FWHM} = \sqrt{8 \ln 2} \cdot \epsilon (\overline{n_0^2})^{1/2}$$
  
=  $\sqrt{8 \ln 2} \cdot \epsilon (F \frac{E}{\epsilon})^{1/2}$   
= 2.355 \cdot (\epsilon E F)^{1/2} (2-21)

Recently, Mann (1966) has measured the Fano factor for lithium drift detectors as a function of the applied electric field. A dependence of the Fano factor on the field was observed. For one detector he measured  $F = 0.16 \stackrel{+}{-} 0.01$  and by extrapolating to infinite electric field he inferred that 0.05 < F < 0.10. Figure 2-9 shows the expected detector contribution to the total resolution for the values F = 0.075 and F = 0.16. Table 2-1 gives the possible resolution and the percentage resolution for both F values at various energies. Use of very high electric fields is limited by deterioration of resolution due to the increase in leakage current with higher electric fields. Leakage currents above one nanoampere affect the resolution noticably.

Besides the detector, the electronics used for amplifying the collected charge represents a significant limitation in obtaining good resolution. At present the best low noise amplifiers have a noise fiqure of 0.75 KeV plus .06 KeV per pF where the capacitance is the total input capacitance. The detector acts as a capacitor with capacity given by:

$$C_{\text{Det}} = 1.1 \frac{KA}{4\pi W} pF \qquad (2-22)$$

where:

K = dielectric constant of material
A = area of the detector
W = depletion layer thickness

for germanium:

$$C_{\text{Det}} = 1.37 \frac{A}{W} \text{ pF}$$
 (2-23)

Goulding (1965f) has presented a very good discussion of noise in a recent paper.

The stability of the electronic system also becomes important since

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Fiqure 2-9 Resolution versus Energy for Various Fano Factors

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| Energy of<br>Gamma Ray | Fano Factor = 0.075      |              | Fano Factor = 0.16 |              |
|------------------------|--------------------------|--------------|--------------------|--------------|
|                        | Resolution (KeV)<br>FWHM | % Resolution | Resolution (KeV)   | % Resolution |
| 250 KeV                | 0.54                     | 0.22         | 0.79               | 0.32         |
| 500 KeV                | 0.76                     | 0.15         | 1.11               | 0.22         |
| 750 KeV                | 0.93                     | 0.12         | 1.36               | 0.18         |
| 1.00 MeV               | 1.08                     | 0.11         | 1.58               | 0.16         |
| 1.50 MeV               | 1.32                     | 0.088        | 1.93               | 0.13         |
| 2.00 MeV               | 1.53                     | 0.076        | 2.23               | 0.11         |
| 2.50 MeV               | 1.71                     | 0.068        | 2.49               | 0.10         |
| 3.00 MeV               | l.87                     | 0.062        | 2.73               | 0.091        |
| 4.00 MeV               | 2.16                     | 0.054        | 3.15               | 0.073        |
| 5.00 MeV               | 2.41                     | 0.048        | 3.52               | 0,070        |
| 6.00 MeV               | 2.64                     | 0.044        | 3.86               | 0,064        |
| 7.00 MeV               | 2.86                     | 0.041        | 4.17               | 0,060        |
| 8.00 MeV               | 3.05                     | 0.038        | 4.46               | 0.056        |
| 9.00                   | 3.24                     | 0.036        | 4.73               | 0.053        |
| 10.00                  | 3.41                     | 0.034        | 4.98               | 0,050        |

Table 2-1 Resolution for Fano Factors of 0.075 and 0.16

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gain shifts of 0.1 % seriously affect the resolution. The use of gain stabilization over the whole system can help reduce the gain shifts of the electronic equipment.

# CHAPTER 3

#### EXPERIMENTAL EQUIPMENT

The experimental equipment developed for producing detectors was ; a lithium evaporation system, drift units and power supplies for drifting crystals, a drift current controller, and two styles of detector holder.

# A. Lithium Evaporation Equipment

The evaporation and diffusion of lithium was done in a CVE-15 vacuum system. The evaporation assembly is shown in Fiqure 3-1a. Lithium was heated in a tantalum evaporation boat of the shape shown in Fiqure 3-1b. The deflector above the boat directed most of the lithium downwards onto the crystal. Around the boat was a stainless steel shield to keep most of the vacuum system clean during lithium evaporation. A hole in the bottom of the shield allowed the lithium to be transmitted to the crystal. A movable stainless steel flag between the boat and the crystal prevented contaminants released during the initial heating of the boat from depositing on the crystal.

The crystal was mounted on a four inch diameter by one quarter inch thick graphite block which was used as the diffusion heater. After evaporation, the lithium was allowed to diffuse into the germanium by heating the block to  $450^{\circ}$ C using a current of 150 amperes at 4 volts.

# B. Drifting Units

The drifting of lithium through the germanium crystals was performed



Figure 3-1 (a) Evaporation Assembly



Figure 3-1 (b) Evaporation Boat

with the crystal mounted on a temperature controlled plate. The drift unit design is based on a system described by Goulding and Hansen (1964). A picture of one of the drift units is shown in Fiqure 3-2a. The crystal was placed on a chrome plated copper block which was mounted, with five other units, on a refrigerated  $(-10^{\circ}C)$  copper plate to provide a heat leak of twenty watts from the plate on which the crystal was placed. The drift unit was heated with a 120 ohm 11 watt power resistor mounted underneath the upper plate. The high voltage drift bias was applied to the crystal by a spring contact made of phosphor bronze and insulated from the rest of the assembly. The drift unit was electrically insulated from the refrigerated plate with a thin sheet of mylar (silicone thermal grease on both sides) so that the drift current passed through the drift current control to ground.

The temperature of the upper plate was monitored with a resistance thermometer. Each drift unit was covered with an inverted 1000 ml glass beaker which was filled with nitrogen during drift to inhibit contamination of the crystal. In Figure 3-2b three of the complete drift units are shown.

This type of drift unit has proven very convenient and reliable for the drifting of crystals.

# C. Power Supply

The power supply used to provide the high voltage bias for drifting is similar to that used by Hansen and Jarrett (1964). The circuit for the power supply is shown in Fiqure 3-3. It can supply up to 100 ma at 1000 volts. A large variable resistor is placed in series with the output to limit the power output. The limit is set with the crystal drifting by adjusting the variable resistor until the output voltage is half of the rectified voltage.

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Figure 3-2 (a) Germanium Drift Unit



Figure 3-2 (b) Three Complete Drift Units



1000 Volt - 100 ma Power Supply



### D. Drift Current Controller

A current controller was designed to maintain the drift current through a crystal to a preset value. The drift current was controlled by suitably heating or cooling the plate on which the crystal was mounted.

The circuit is based on that of Hansen and Jarrett (1964) and is shown in Figure 3-4.

The controller measured the voltage across a resistor in series with the drift current and varied the power sup-lied to a heater resistor underneath the drift plate so as to maintain this voltage constant. The drift current level was set by changing the resistor in series with the current. The lower the resistance the higher the the drift current since the controller maintains the voltage across the resistor at the value -7.5 volts. Table 3-1 gives the value of the resistor for the various drift currents.

A differential amplifier compared the voltage across the resistor to a set level. Following the amplifier, the circuitry differs significantly from that described by Hansen and Jarrett (1964). In the UBC system, the output of the amplifier controlled the frequency of a unijunction transistor oscillator. The oscillator in turn triggered a silicon controlled rectifier (SCR) which was in series with the resistor under the drift plate.

The frequency of the oscillator when the drift current was balanced was less than sixty cycles per second so that the SCR was only on during part of the rectifying cycle. The oscillator controlled the power to the heater since the higher the oscillator frequency the more often the rectifier was on and supplying power to the heater. The maximum temperature of the drift plate could be set by adjusting the maximum oscillator frequency with

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Figure 3-4 U.B.C. Current Controller

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| Drift Current | Resistances Used (ohms) | Total Resistance (ohms) |  |
|---------------|-------------------------|-------------------------|--|
| (mA)<br>5     | 100* + 150 + 1100       | 1350                    |  |
| 10            | 100* + 390 + 220        | 710                     |  |
| 15            | 100* + 390              | 490                     |  |
| 20            | 100* + 150 + 47 + 82    | 379                     |  |
| 25            | 100* + 150 + 47         | 297                     |  |
| . 30          | 100* + 150              | 250                     |  |
| 40            | 100* + 27 + 27 + 39     | 193                     |  |
| 50            | 100* + 27 + 27          | 152                     |  |
| 60            | 100* + 27               | 127                     |  |
| 70            | 100* + 12               | 112                     |  |
| 80            | 100*                    | 100                     |  |
| ·             |                         | :_                      |  |

\* - 5 watt resistor

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the variable resistor  $R_{11}$  (see Figure 3-4).

If the drift current was too low the differential amplifier output would trigger the oscillator so that the rectifier was on most of the time and therefore the drift plate would be heating. On the other hand, if the drift current was too high the oscillator would be off and the drift plate would therefore cool. If the drift current was at the selected value the oscillator would trigger just enough to maintain the temperature.

The advantages of this controller were that the heating element was a passive element, a power resistor, the maximum temperature was adjustable, and the control was continuous from full on to off.

#### E. Detector Holders

The detector holders used for mounting the finished detectors were of two types similar to those described by Miner (1965).

The first type, Figure 3-5a, was used for detector testing and for counting with radioactive sources. It was convenient for testing drifted crystals as it was small thus making it easy to pump, cool, and keep clean. It was also convenient when used with radioactive sources which could be mounted easily under the holder.

The second holder, Fiqure 3-5b and Fiqure 3-6,was more suited to studies with the UBC Van de Graaff accelerator as the detector was mounted horizontally.

Both holders use a Linde CR-10 liquid nitrogen dewar which normally retains coolant for about a week.

A one liter per second VacIon pump, Varian Model No. 913-0008, was used to maintain a pressure of around 2 x  $10^{-6}$  torr in the holder.

Electrical connections to the preamplifier were made by inserting

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Figure 3-5 (a) Vertical Detector Holder



Figure 3-5 (b) Horizontal Detector Holder



Figure 3-6 Detector Holder

a lead through an insulating Kovar connector on the detector holder. When the field-effect transistor amplifier was used a four pin Kovar connector was used to make electrical connections.

### F. Detector Preamplifier

The preamplifier used initially was the Ortec Model 203-101XL, which used vacuum tubes as the active elements. This was later replaced by a preamplifier utilizing a cooled field-effect transistor (Goulding 1966). The circuit, illustrated in Figure 3-7, was constructed by D. Dalby and was used because of its improved noise characteristics.

With the FET preamp the signal from the detector went to a 2N3823 FET which was mounted inside the holder on a stainless steel screw two cm from the cold finger. The detector was insulated electrically from the cold finger by using a thin sheet of nylon between two sheets of indium with films of high vacuum grease between sheets.



### CHAPTER 4

#### DETECTOR FABRICATION PROCEDURE

The following procedure was used to prepare the lithium drift detectors.

The starying material was a zone-levelled, gallium doped germanium ingot of 5.5 ohm-cm resistivity and sixty microsecond carrier lifetime.<sup>5,6</sup> The ingot was about 15 cm in length with a cross section as shown:

actual size

For slicing, the ingot was mounted on a graphite block with Apiezon black wax and cut on a Micro-Mech precision diamond saw to the desired thickness. The graphite block provided a shock mount for the crystal during cutting. The maximum cut depth per saw blade pass was prevented from exceeding six mm to reduce crystal damage during cutting.

The crystal was cut to a thickness of from six to ten mm and then lapped on both faces with 800 grit alumina grinding powder to remove crystal damage from sawing. The crystal was then cleaned with TCE (trichloroethylene) and methyl alcohol using Johnson cotton Q-Dabs for wiping the crystal.

5. from Sylvania Electric Products, Towanda, Penn.

6. excellent material (20 ohm-cm and 250 micrsec lifetime) was obtained from Société Générale Métallurique de Hoboken, Brussels, Belgium The crystal was then painted on the edges and one face with Aquadag (colloidal graphite in water). This treatment inhibited lithium diffusing into the edges and also helped to produce good thermal contact with the heater on the bottom. When the Aquadag was dry the crystal was ready for the evaporation of lithium onto the unpainted face.

A piece of lithium metal about 1.5 cm x 0.5 cm x 0.3 cm was cut, washed with TCE, blown dry with nitrogen, and placed in the tantalum evaporation boat in the vacuum system. The stainless steel shield was put around the boat and the crystal was placed on the graphite heater under the hole in the shield.

The system was then evacuated to a pressure of around 2 x  $10^{-6}$  torr. The current supply to the evaporation boat was turned on and raised slowly until 140 amperes (7 amperes on the panel meter) was flowing through the boat. When the lithium deposited on the flag turned from black to grey the flag was moved aside and lithium was deposited onto the crystal for one minute.

The evaporation bell jar was closed off from the pumping system and the heater power of 600 watts turned on. When the thermocouple attached to the heater read  $200^{\circ}$ C, nitrogen was let into the bell jar. The heater power was adjusted to give a temperature of  $450^{\circ}$ C for seven minutes and then turned off. Figure 4-1 shows a typical temperature versus time curve. This procedure gave a diffused lithium layer about 0.5 mm deep.

When the crystal had cooled, the excess lithium was washed off with distilled water and the Aquadag was removed. The crystal was given a fifteen second etch which was quenched with distilled water. The resistivity of the lithium surface was measured with a four point probe. If the resistivity of the surface was above 0.2 ohm-cm the lithium had not diffused correctly

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and the lithium evaporation procedure was repeated.

If the surface resistivity was acceptable the crystal was etched for a minute in an etch solution of  $3:1 \text{ HNO}_{3}$ : HF with a small amount of red fuming HNO<sub>3</sub> added to speed the start of the etch. The etch was quenched with deionized distilled water and then the crystal was rinsed with methyl alcohol and blown dry with nitrogen.

Indium gallium eutectic was applied to the crystal faces and the crystal was placed lithium side down on a drift unit. After the cover was put on, the drift unit was filled with nitrogen; heated to  $30^{\circ}$ C, and 100 volts reverse bias applied. After one hour the drift voltage was increased to around 500 volts and the current demand switch adjusted (usually 15 ma) to give a drift temperature around  $35^{\circ}$ C.

During drift the current demand was gradually increased to maintain a drift temperature above 30°C. If the diode junction broke down (characterized by an adrupt fall in temperature) it was removed and given a surface treatment as follows. After removing the indium gallium eutectic with a Q-Bud wetted with TCE, the faces were taped with #471 Scotch tape and the crystal given a one minute etch after which it was quenched with methyl alcohol. After blowing the crystal dry with nitrogen and removing the tape the crystal was replaced on the drift unit and the same procedure followed as for a new crystal.

If the crystal still would not drift it was removed from the drift unit and the drifted region was made visible by reverse biasing the crystal in a weak copper sulphate solution (20 grams per liter of water). The drifted region does not stain where as the undrifted region is stained a brown colour. If the junction was distorted at some point, the distorted area was sawn off with the diamond saw. The sawn surface was lapped, the

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faces taped, the crystal etched for one minute, quenched in methyl alcohol, and then replaced on the drift unit.

If the crystal still would not drift it was given a "frost test". <sup>7</sup> This consisted of placing the crystal in a clamp (insulated so reverse bias could be applied), immersing it completely in liquid nitrogen for seven seconds, blowing on it to form a layer of frost; then reverse biasing to a current of sixty ma. If the frost melted preferentially in one area it indicated that the current was flowing across the crystal in that area predominantly. This area was then removed by sawing and the same procedure followed as in the previous paragraph to put the crystal back on the drift unit.

When the width of the drifted region was estimated using Fiqure 2-8 to be about 1 mm from the undrifted face the crystal was removed and stained. If the crystal was not the desired depth the etch treatment described above was performed and the crystal replaced on the drift unit for continued drifting. If, however, the crystal had drifted the desired depth it was given a surface treatment and replaced on the drifter for twelve hours at low current demand (5 ma) and 500 volts. The temperature characterizing these conditions was about -5°C. This postdrift was done to let the lithium concentration adjust to the reduced generation current and to let the lithium ions pair with the acceptor impurities.

To test the drifted crystal the gate and drain leads of the FET in the holder were shorted so that the leakage current versus voltage characteristic of the crystal could be measured. The crystal was given a one minute etch (faces taped) after which the crystal was quickly moved to a beaker of

7. E. Kashy and M. Rickey, Rev. Sci. Instr. <u>35</u>, 1364 (1964).

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methyl alcohol for fifteen seconds and then blown dry. It was immediately mounted in a holder with the lithium side upwards and a small amount of eutectic placed on the lithium side where the amplifier contact pressed on the crystal. The holder was evacuated and, when the pressure was  $2 \times 10^{-6}$ torr, liquid nitrogen was put in the cold finger of the holder.

The lekage current versus voltage characteristic was measured using the arrangement shown in Figure 4-1. Usually several treatments of the sort described above were required before the leakage current was below ten nanoamps at the operating voltage (about 75 volts per mm). When this was achieved the gate-drain shorting wire was removed and the holder re-evacuated, cooled and the VacIon pump valve opened and the roughing valve closed. The amplifier was turned on, detector bias voltage applied, and the detector was tested for resolution using Co<sup>57</sup> and Cs<sup>137</sup> radioactive sources. The fabrication procedure was now completed and the detector ready for operation.





#### CHAPTER 5 - PRESENTATION OF RESULTS

# A. Silicon Detector Fabrication

Prior to making germanium detectors several silicon lithium drift detectors were produced. It was found relatively easy to fabricate silicon detectors so they served the purpose of testing the diffusion and drifting apparatus for faults before trying to prepare germanium detectors.

The procedure followed for the fabrication of silicon detectors was similar to that of Lothrop and Smith (1965). The procedure differed in several respects from that used for the preparation of germanium detectors. The diffusion temperature was 350°C and the diffusion time was two minutes. The lithium drifting was done on a plate as described by Lothrop and Smith (1965) except that the heating was performed using the drift controller described in Chapter 4. Typical drift temperatures were 110°C and the drift current was four milliamperes at 500 volts. The surface treatment was the same as used by Lothrop and Smith. A typical cross section of the compensated region is shown in the following diagram.



The silicon detectors produced by this means had an active volume of about 0.7  $\text{cm}^3$ . (12 mm. in diameter by 2 mm. deep).

The drifting rate of lithium in silicon is approximately half of that in germanium so silicon detectors are rarely made with a compensated depth greater than 5 mm.

A Cs<sup>137</sup> gamma ray spectrum taken with a silicon detector at 77<sup>°</sup>K with a FET preamplifier is shown in Figure 5-1. The counting rate in the full energy (661 keV) channel relative to that of a channel in the Compton background is 4%. The resolution of the peak is 4.8 KeV FWHM (full width at half maximum).

Because of their low gamma ray detection efficiency, silicon devices are rarely used as gamma spectrometers. For detection of charged particles, on the other hand, they are widely used because of their easy fabrication, stable characteristics, and, most important, their high resolution performance, even when operated at room temperature.

# B. Germanium Detector Production

The final quality of a detector is very dependent on the characteristics of the germanium ingot from which it is fabricated. Except for the last one described, all detectors mentioned in this thesis were produced from the same ingot which was obtained from Sylvania Electric Products.

Initial measurements on a detector made from one end of this ingot gave moderately good results. Two more detectors were fabricated, with difficulty, from the same end of the ingot but, despite very careful techniques, the remaining two thirds of the ingot produced no useable detectors.

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Figure 5-1 Cs<sup>137</sup> Gamma Ray Spectrum with Silicon Detector

During the lithium drift stage many etching and sawing operations were required and, although a drift depth of 5 mm. was obtained, the crystals still did not make usable detectors because of high leakage current. Repeating surface treatments, sawing off various areas, and rediffusing lithium did not reduce the leakage current o a useable level. After several months of negative results a new ingot was obtained from Hoboken of Belgium which produced a very good detector with the first slice. One characteristic of the ingot which would seem to be important is the initial resistivity. The Sylvania ingot had a resistivity of 5 ohm-cm while the Hoboken ingot had a resistivity of 20 ohm-cm.

The first germanium detector produced from the Sylvania ingot had an instrinsic resolution of 4.0 KeV for 661 KeV gamma rays at an operating voltage of 175 volts. The depletion depth was about 4 mm. giving an active volume of approximately 1 cm<sup>3</sup>. Unfortunately this detector was damaged when the vacuum pump for the detector holder failed and became contaminated. At the time it was not feasible to store the detector at liquid nitrogen temperatures while the pump was repaired so the detector was destroyed.

The second detector had a depletion depth of 5 mm. and an active volume of about 0.5 cm<sup>3</sup>. The energy resolution at 661 KeV was 4.0 KeV (intrinisic resolution 1.9 KeV) at a bias voltage of 200 volts.

The third detector also had a depletion depth of 5 mm. but the area was larger giving an active volume of 2.0 cm<sup>3</sup>. At a bias voltage of 225 volts it gave an energy resolution of 5.1 KeV (4.5 KeV intrinsic resolution) for 661 KeV gamma rays.

The fourth and best detector, which was prepared from the Hoboken ingot, had an active volume of  $1.7 \text{ cm}^3$  and a depletion depth of 5 mm. The energy resolution obtained with this detector is summarized in the following table.

| Total Resolution<br>(FET preamp) | Intrinsic Resolution  |
|----------------------------------|---|
| 2.5 KeV                          | <b>1.3</b> Kev  |
| 2.6 KeV                          | 1.5 KeV   |
| 2.9 KeV                          | 2.0 KeV   |
| 4.1 KeV                          | 3.5 KeV   |
| 5.2 KeV                          | 4.9 KeV   |
|                                  | Total Resolution<br>(FET preamp)<br>2.5 KeV<br>2.6 KeV<br>2.9 KeV<br>4.1 KeV<br>5.2 KeV |

Figures 5-2 and 5-3 show similar  $Cs^{137}$  spectra taken with detectors #2 and #4. The higher resolution of detector #4 compared to the other detectors is clearly seen by comparing the two figures. The improved resolution of the fourth detector probably resulted from the use of a better germanium ingot.



Figure 5-2  $Cs^{137}$  Spectrum with Detector # 2

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### C. Detector Operation

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When using germanium detectors it is important to optimize the detector resolution.

The detector resolution is dependent on the detector Figure 5-4 shows a typical leakage current versus bias voltage. bias voltage graph. The best operating voltage is a little below the voltage where the leakage current increases rapidly. Figure 5-5 Jure gives the shape of a 661 KeV (Cs<sup>137</sup>))gamma ray peak for various bias voltages obtained with detector #2. Below 200 volts the resolution increased as the voltage was increased because the charge collection efficiency increases with electric field. The peaks are very asymmetric with a tail on the low energy side due to incomplete charge collection for some of the gamma rays. Above 200 volts, on the other hand, the peak broadens rapidly due to a rapid increase in the leakage current. The peak is symmetric but much wider. The optimum bias voltage is, therefore, relatively easily found by increasing the bias voltage until the asymmetry in the spectrum peaks disappears and the peak becomes symmetric but does not widen. With good detectors the leakage current remains low at high electric fields and therefore the operating voltage is not as critical (electric fields are typically 100 volts per mm.). For high energy gamma rays (greater than 3 MeV), however, careful optimization of the bias voltage can increase the resolution considerably.

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Figure 5-4 Typical Leakage Current versus Bias Voltage



Figure 5-5 Peak Shape for Various Bias Voltages

The replacement of the Ortec 101XL preamplifier with the cooled FET preamplifier reduced the electronic noise contribution from 3.2 KeV to 2.1 KeV. A single differentiation time constant of  $1.0\mu$  sec was found to yield the lowest noise.

The gamma ray spectra shown in Figures 5-6 to 5-10 were obtained using detector #4 with an FET preamp and illustrate the high resolution achievable with germanium detectors. The  $\mathrm{Co}^{57}$  spectra of Figure 5-6 shows the resolution obtained at low energy. The separation of the two peaks is 14 KeV and the resolution is 2.5 KeV. At low energy most of the peak width is due to electronic noise.

The Cs<sup>134</sup> spectra of figures 5-7 and 5-8 and the Eu<sup>154</sup> spectrum of Figure 5-9 vividly illustrate the value of high resolution in the separation and measurement of complex gamma ray spectra. Figure 5-8 illustrates the region from channel 318 to 332 of Figure 5-7 with the background subtracted. The two gamma rays, which are 6.7 KeV apart, are clearly resolved. In Figure 5-9 the many gamma rays of the Eu<sup>154</sup> are clearly shown.

The full energy peak (2614 KeV), the first escape (2103 KeV), and the double escape peak (1592 KeV) of the RdTh spectrum are shown in Figure 5-10. The number of counts in the double escape peak (with background subtracted) is 30 times the number in the full energy peak. For gamma ray energies above 2 MeV the double escape peak is the dominant peak and the full energy and single escape peaks give a

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Figure 5-6 Co<sup>57</sup> Spectrum

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convenient check of the energy calibration of the analyzer since the energy difference between the peaks is 511 KeV.

In Figure 5-11 the square of the resolution is plotted as a function of gamma ray energy for detector #4. A crude estimate of the Fano factor obtained from this data is 0.5 which is considerably higher than that measured by Mann (1966). The large Fano factor obtained here is at least partially attributable to artificial broadening of the peaks due to electronic instability and drifting since the counting rates were fairly high and gain stabilization was not used.

Preliminary efficiency measurements were made with detector #4 at different energies. The results are tabulated in Table 5-1. Fow low energy gamma rays the efficiency is high but it falls off rapidly so that above 2.5 MeV the full energy peak efficiency is less than 0.1%. The double escape peak efficiency, however, for gamma ray energies above 2 MeV remains almost a constant at a value of 0.3% for this detector.

The linearity of the amplifier (Ortec 201 Multi-Mode) and the pulse height analyser (Nuclear Data ND-160) were measured using  $Cs^{134}$  and  $Eu^{154}$  spectra (figures 5-7 and 5-9). The peak positions were calculated and, using the tabulated energies for the gamma rays, a least squares straight line fit of the gamma ray energy as a function of channel position was performed. The results are presented in Table 5-2. In Both the  $Cs^{134}$  and  $Eu^{154}$  spectra the deviation from a straight line was less than the quoted accuracy of the gamma ray

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| Table S | 5-1 |
|---------|-----|
|---------|-----|

|    | Eg.<br>Source    | E <sub>n</sub> (MeV) | Strength | Distance | #of $oldsymbol{	au}$ 's through Detector | #Counted            | <u>Eff</u> . |
|----|------------------|----------------------|----------|----------|--|---------------------|--------------|
| 1) | Co <sup>60</sup> | 1.172                | 49:3µCi  | 14.5 cm  | $1.2 \times 10^{7}$                      | $4.0 \times 10^4$   | .32%         |
|    | Co <sup>60</sup> | 1.332                | 49.30Ci  | 14.5 cm  | $1.2 \times 10^{7}$                      | $3.6 \times 10^4$   | .29%         |
| 2) | RdTh             | 2.614                | 6.65µCi  | 7 cm     | 7.2 x $10^6$                             | $6.2 \times 10^{2}$ | .08%         |
|    | D.E.             | 1.592                | 6.65 Ci  | 7 cm     | 7.2 x 10 <sup>6</sup>                    | $2.2 \times 10^3$   | .31%         |

## Table 5-2a Linearity for Eu

| <br>Channel Position | Energy      | Energy Calculatedfrom | Energy Difference |
|----------------------|-------------|-----------------------|-------------------|
| 86.9                 | 245.0 KeV   | 243.6 KeV             | - 1.4 KeV         |
| 161.4                | 345.0 KeV   | 345.5 KeV             | + 0.5 KeV         |
| 210.0                | 412.0 KeV   | 412.0 KeV             | 0.0 KeV           |
| 234.0                | 445.0 KeV   | 445.2 KeV             | + 0.2 KeV         |
| 481.1                | 782.0 KeV   | 783.1 KeV             | + 1.1 KeV         |
| 617.2                | 969.0 KeV   | 969.3 KeV             | + 0.3 KeV         |
| 706.8                | 10'32.0 KeV | 1032.0 KeV            | 0.0 KeV           |
| 726.0                | lll8.0 KeV  | 1118.2 KeV            | + 0.2 KeV         |
| 942.9                | 1416.0 KeV  | 1415.1 KeV            | - 0.9 KeV         |
|                      |             |                       |                   |

Energy = 124 KeV + 1.368 KeV/channel

Table 5-2b Linearity of Cs<sup>134</sup> Spectrum

| Channel Position | Energy     | Energy Calculated | Energy Difference |
|------------------|------------|-------------------|-------------------|
|                  |            |                   |                   |
| 322.8            | 563.0 KeV  | 563.3 KeV         | + 0.3             |
| 327.3            | 569.7 KeV  | 569.4 KeV         | - 0.3             |
| 353.1            | 605.4 KeV  | 604.7 KeV         | - 0.7             |
| 671.5            | 1039.0 KeV | 1039.9 KeV        | + 0.9             |
| 766.2            | 1168.0 KeV | 1169.3 KeV        | + 1.3             |
| 910.5            | 1368.0 KeV | 1366.5 KeV        | - 1.5             |
|                  | · .        |                   |                   |

1

Energy = 122 KeV + 1.367 KeV/channel.

energies and the accuracy of the peak determination. From this data the integral linearity of the system was estimated to be better than 0.2% over the channel range 100 to 1000 channels.

## CHAPTER SIX - CONCLUSIONS

The fabrication of germanium lithium drift detectors, although basically a simple process, requires considerable care and cleanliness to produce high quality gamma ray spectrometers.

The major problems in fabrication are the initial quality of the material and the control of the surface states. If the original germanium ingot is damaged or of poor quality considerable effort can be wasted trying to make detectors from it. Controlling the surface state of the exposed compensated region is a poorly understood technique. The leakage current of the detector is determined primarily by the surface leakage. If a better way was found to control and maintain neutral surface states, such as a protective SiQ<sub>2</sub> layer, the applied electric field could be increased. The use of higher electric fields could increase the charge collection efficiency, and thus improve the energy resolution of the detector.

Development of lower noise and higher stability electronics will also improve the total resolution. Optimization of FET preamplifiers and developments in parametric amplifiers should reduce the present electronic noise.

Statistical processes, however, will limit the ultimate system resolution to around 1 KeV at 1 MeV for germanium detectors (see Figure 2-9). Other semiconductor materials characterized by smaller energy gaps, such as GaAs may give better resolution but, at present, such materials of sufficient purity are not available.

The efficiency of germanium detectors is limited by the

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active volume of the detector. Detector efficiency should gradually improve as higher quality germanium and better fabrication techniques (such as coaxial and two way drifting) make larger active volumes easier to produce and techniques for stacking of several detectors are improved.

Because of the superior resolution and high efficiency of germanium lithium drift detectors they are rapidly replacing other detectors as the major experimental instrument for gamma ray spectrometry. A. Recipe for etch:

Mix the following ingredients in the following order:

7 lbs. of concentrated nitric acid (70%).

2 lbs. of 48% hydrofluoric acid.

 $\frac{1}{2}$  lb. of red fuming nitric acid.

B. Ga-In Eutectic:

Prepare with 12% by weight of gallium.

C. Etch resistant tape:

Scotch #471, 3 M Company. (local supplier, Black Bros.).

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