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INTERIM ENGINEERING REPORT

SHORT WIDE ANGLE, 1-1/2 INCH ELECTROSTATIC IMAGE DISSECTOR WITH PARALLEL PLATE RESISTIVE STRIP ELECTRONIC MULTIPLIER

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1. INTRODUCTION

The purpose of this contract was to develop and fabricate a small, purely electrostatic electron strip multiplier for use in small image dissector tubes designed for space navigation systems.

For the proposed application an electron multiplier one inch in length and with a gain of 10^6 was required.

The multiplication process can be described briefly as follows: The multiplier strip is mounted at an angle to the equipotential lines in a parallel field. (Figure 1). Primary electrons from a photoemissive cathode or a thermally excited source are directed at the negative end of the multiplier strip. The secondary electrons, released from the strip by the primaries, follow parabolic paths and land at a more positive point of the strip. The secondary emission cycle is then repeated.

Theoretical analysis of the secondary electron trajectories indicated that the angle of the strip with the normal to the field should be close to 20°. This was confirmed in the experiments.

The materials used for multiplier strips, besides having the necessary resistive and secondary emissive characteristics had to be stable in the presence of the alkali elements commonly used in photoemissive devices.

It was found in limited experiments that the resistance of gallium arsenide plates, cut from single crystals, was in the desired range but no multiplication could be obtained from either the plain or magnesium oxide coated plates. Thin films of tin oxide, nichrome, and silicon on lime soda glass slides with or without coatings of good secondary emitters, were evaluated. Of these, plain evaporated silicon with an overall resistance of 10^8 to 10^9 ohms proved to be the most successful. The high value of resistance was necessary in order to minimize the power dissipation and the resultant joule heating of the strip. The maximum gain obtained from evaporated silicon strip was approximately 10^5.

2. THEORETICAL CALCULATIONS

The following discussion includes equations and calculations which were developed for the strip multiplier to determine the approximate strip slope and number of loops required to obtain a suitable overall gain with a selected voltage gradient. Figure 1 is a sketch, which briefly outlines the geometry of the strip multiplier.

In the development of the equations, certain assumptions were made to reduce the complexity of the theoretical treatment. It is first assumed that the initial velocity of electrons in the direction normal to the condenser plates is zero in calculations of average electron velocity. This assumption is reasonable, because the actual initial velocity is small compared with the final velocity resulting from the acceleration between plates. This means that only those secondary electrons leaving the strip in a direction parallel to the plates, i.e., at an angle (α) with respect to the strip, are considered in determining the loop length. Since α is a relatively large angle, the number of electrons emitted at/or close to α should be a high percentage of the maximum emission normal to the strip surface. Hence, the result should prove to be a close approximation of the average loop length.

Second, it is assumed that the initial velocity in the direction parallel to the plates is equal to one electron volt. Since the emission velocities essentially follow a maxwellian distribution, other velocities could be considered, but would provide no significantly better approximation for the average electron trajectory.

Although the above assumptions are made, it should be pointed out that variations in loop length will occur as a result of the various electron emission angles and velocities.

Let us consider trajectories of electrons accelerated normally between two parallel condenser plates in a uniform electrostatic field. The final energy of the electron is given by:

$$E = 1/2\ mv_f^2 = e\ V\ \text{total}$$

where

E = Final electron energy (ergs)

m = Electron mass = 9.1×10^{-28} grams

V_f = Final electron velocity (cm/sec.)

e = Electronic charge (coulombs)

V total = Voltage between plates (volts)

ρ = 1×10^{7} ergs/joule

Hence, the final velocity is found to be

$$v_f = \left(\frac{2\rho e\ \ V\ \text{total}}{m}\right)^{1/2} \qquad \text{where } \frac{e}{m} = 1.759 \times 10^{8}\ \frac{\text{coulombs}}{\text{gram}}$$

Since it is assumed that the initial velocity normal to the plates is zero, the average velocity of these electrons is given by

$$v_{av} = \frac{v_f}{2} = 1/2 \left(\frac{2\ \rho\ e\ \ V\ \text{total}}{m}\right)^{1/2}$$

The average velocity can also be expressed as $v_{va} = \frac{S}{t}$ where S is the distance travelled.

Hence, the time of flight of the electron between the plates can be written as

$$t = \frac{S}{v_{av}} = \frac{2S}{v_f} = 2S\left(\frac{2\rho e\ \ V\ \text{total}}{m}\right)^{-1/2}$$

Now let us consider electrons emitted in a direction parallel to the plates. Since there is no field component in this direction, no acceleration takes place and the average velocity is equal to the initial velocity. This direction will be referred to as the "r" direction. The distance traversed by an electron in the "r" direction is given by:

$$r = v_r t$$

where v_r is the electron velocity in the "r" direction and t is the time of flight discussed above. This velocity can be expressed as

$$v_r = \left(\frac{2E_r}{m}\right)^{1/2}$$

where E_r is the energy of the electrons emitted in the "r" direction.

Figure 1 shows that the loop length or the distance between loop nodes along the strip is defined by the vector sum of the "r" and "s" distances travelled during the time of flight (t). The loop length is given by:

$$B = \frac{S}{\sin \alpha}$$

where $\alpha = \tan^{-1} \frac{S}{r}$

and $S = \frac{L}{N}$

where L is the perpendicular distance between plates and N is the effective number of multiplier stages.

The effective stage voltage can be written as:

$$V = \frac{V\ \text{total}}{N} = \frac{S}{L} \quad V\ \text{total}$$

Since the overall gain (G) can be written as a function of the stage gain, i.e.,

$$G = \gamma^N$$

the stage gain required to obtain an overall gain G can be determined from the equation

$$\gamma = \text{anti log} \left[\frac{\log_{10} G}{N}\right]$$

With the equations given in the preceding paragraphs, loop length and strip angle approximations can be calculated as follows:

Assuming that L, the distance between plates = 2.5 cm,

G, the overall gain = 1×10^6

V, the overall voltage = 1600 volts

Vs, the stage voltage = 32 volts

(E_r), the energy of electrons emitted in the "r" direction = 1 electron volt = 1.6×10^{-12} ergs

The number of stages (N) is then given by

$$N = \frac{V}{Vs} = \frac{1600}{32} = 50 \text{ stages}$$

The secondary emission ratio required to obtain a gain of 1×10^6 with 50 stages of amplification is calculated as

$$\gamma = \text{anti log} \left(\frac{\log_{10} G}{N}\right) = \text{anti log} \left(\frac{\log 1 \times 10^6}{N}\right)$$

$$\gamma \sim 1.13$$

This secondary emission yield should be obtainable from both cesium antimony and magnesium oxide secondary emission surfaces at the stage voltage indicated.

Since we have set the number of stages at 50 and the total distance between plates at 2.5 cm the distance (S) indicated in Figure 1 can be caluclated by

$$S = \frac{L}{N} = \frac{2.5}{50} = 5 \times 10^{-2} \text{ cm}$$

where S is the component of the electron trajectory normal to the condensor plates, associated with one stage of amplification or one loop.

Knowing S and V_s the time of flight for the electron to form one loop can be obtained by

$$t = 2S \left(\frac{2\rho e V_s}{m}\right)^{-1/2} = 2 \times 5 \times 10^{-2} \left(2 \times 1.759 \times 32 \times 10^{8} \times 10^{7}\right)^{-1/2}$$

$$t \approx 3 \times 10^{-10} \text{ sec.}$$

Using the equation

$$v_r = \left(\frac{2Er}{m}\right)^{1/2}$$

and setting $Er = 1.6 \times 10^{-12}$ ergs,

the velocity of the electrons in a direction parallel to the condensor plates can be calculated as follows:

$$v_r = \left(\frac{2 \times 1.6 \times 10^{-12}}{9.1 \times 10^{-28}}\right) \approx 5.92 \times 10^{7} \text{ cm/sec}$$

and the distance (r) can be obtained by

$$r = v_r t = 5.92 \times 10^{7} \times 3 \times 10^{-10} \approx 1.78 \times 10^{-2} \text{ sm}$$

The strip slope can now be determined by the equation

$$\tan \alpha = \frac{S}{r} = \frac{5 \times 10^{-2}}{1.78 \times 10^{-2}} \quad 2.82$$

$$\alpha = 70.5°$$

and the loop length (B) is calculated as

$$B = \frac{S}{\sin\alpha} = \frac{5 \times 10^{-2}}{.943}$$

$$B \approx 5.3 \times 10^{-2} \text{ cm}$$

The total strip length (b) is given by

$$b = \frac{L}{\sin\alpha} = \frac{2.5}{.943} = 2.65 \text{ cm}$$

The values obtained above should be close approximations to the actual strip performance, but it should be pointed out that the peak characteristics can only be determined experimentally.

Although the required gain of 10^6 was not achieved, the experiments, conducted in this investigation demonstrated the feasibility of using the strip multiplier in photoemissive tubes.

Materials limitations and the necessity of using high accelerating voltages much in excess of 1600V prevented the realization of the required gain.

3. RESISTIVE STRIP DEVELOPMENT

One object of this contract was to develop resistive electron multiplier strips, exhibiting secondary emission properties and stable resistance in the range of 10^8 ohms.

In the process of resistive strip development several approaches, employing various resistive and secondary emissive materials, were considered.

During the initial experiments, the possibility of using magnesium oxide, a good secondary emitter, for the strip multiplier surface, was investigated.

Films of magnesium oxide and silver doped magnesium oxide on soda lime glass were made and their resistive properties evaluated. The resistance of these films proved to be too high for the proposed application. Soda lime glass was selected for the experiments since it was necessary to avoid the use of glasses containing lead as these react with the alkali elements which would be used in devices utilizing the multiplier. Vacuum deposited nichrome was tried next for resistive strip application. Continuous nichrome films with an optical transmission of 80% had a resistance of only 3×10^5 ohms. Since such a thin layer could not carry the high conduction current without overheating and ultimate breakdown a "ladder" configuration of nicrhome film was adapted as shown in Figure 2. This type of resistive film strip with cesium antimony secondary emissive layer was used in first four experimental devices.

The initial resistance of the first batch of "ladder" type nichrome films of about 8×10^6 ohms was too low for use in the strip multiplier devices although one of them was used in the first experimental tube.

Further work on "ladder" type nichrome films resulted in resistive strips with maximum resistance, varying between 50 and 90 megohms. However, these films were unable to withstand voltages necessary to attain the required gain.

In search for other applicable resistive strip materials experiments were conducted to evaluate nesa and silicon films. Nesa films of the required resistance (10^8 ohms) did not appear to form a continuous layer and in addition the voltage current relationship of the films was non linear. In view of these undesirable characteristics and the instability of nesa in the presence of the alkali elements this approach was abandoned.

Vacuum deposition of pure silicon on glass slides yielded films which exhibited stable resistance at voltages up to 4 kilovolts both in vacuum and in air. With these, practically any desired value of resistance was obtained in the range from 10^3 to 10^9 ohms, by careful control of deposition rate, temperature of the substrate and pressure. Of all the materials investigated, evaporated silicon films proved to be most suitable for multiplier strip application.

The possibility of using strips of solid silicon and gallium arsenide was considered. Although some of the samples exhibited suitable resistance characteristics, the secondary emission, from both uncoated and magnesium oxide coated strips, was very low.

4. EXPERIMENTAL TUBE DEVELOPMENT

Initially it was intended that an electrostatically focussed electron gun would be used as the source of primary electrons in strip multiplier experiments. However, the difficulties encountered in controlling the extremely small currents prompted the development of experimental tubes using photoemissive cathodes for the electron source. In these, it was possible to produce a low density small cross section beam of electrons with which to evaluate the electron multiplier design and strip characteristics.

This approach also ensured that the strips were exposed to similar environmental conditions to those which would occur in their ultimate use.

The experimental device was designed around the image section of the CBS Type CL 1147 Image Dissector. No deflection system was included since the position of the electronic spot at the negative end of the multiplier strip, which was placed directly below the aperture, could be controlled by physical displacement of an optical image at the photocathode. The area on which primary electrons could land on the multiplier was determined by an aperture 0.030 by 0.140", the major axis of which was parallel to the plane of the multiplier strip. Figure 3 is a schematic of the design.

Some of the devices were made so that the angle which the strip made with the electric field could be varied. This enabled rapid confirmation of the angle at which maximum gain occurred.

The initial design proved unsatisfactory owing to leakage between the field shaping electrodes being in the same order as the strip multiplier currents. In addition test measurements indicated that electrons from the strip were being collected by the field shaping electrodes. Redesign of the collector support eliminated these problems.

During the tube experiments several changes were made in the field shaping electrode configuration in order to study their effect or gain since the optimum theoretical approach had to be compromised in the mechanical design. The changes included using a multiplicity of shaping electrodes, using the high potential field shaping electrode as the collector and changes in the relative position of the multiplier strip within the electric field.

5. EXPERIMENTAL TUBE: TEST AND DISCUSSION

The design objective was to obtain a minimum gain of 10^6 at maximum potential of 1600 volts applied to the multiplier strip.

All the experimental strip multiplier tubes were tested with the image section energized as shown in Figure 3. The collector potential was set about 100 volts positive with respect to the bottom end of the strip.

The measured gain of the first strip multiplier tube, Serial No. 607A was low due to leakage paths between the tube elements. In addition low nichrome film resistance (8×10^6 ohms) prevented the application of high voltages which were necessary in order to obtain practical gains.

Figure 4 shows the strip conduction current versus strip voltage curve.

Figure 5 shows the curves of gain versus strip voltage for this tube.

The gain curves of Figure 6 were obtained when retesting the same tube after cleaning up of leakage paths. The strip resistance measured during the retesting varied from 50 to 200 megohms depending on the applied voltage. The maximum gain upon retest was 136,000. This was measured when the strip was at 4° with respect to the tubes axis when the grid potential was near that of the negative end of the strip.

In tube Serial No. 610F a nichrome film resistive strip of 80×10^6 ohms was used. The angle, that the strip was making with the axis of the tube or normal to the condenser plates, was fixed at 19.5°. The test data of this tube indicated that the grid potential had a significant effect on the overall performance of the strip multiplier. Figure 7 shows a curve of gain versus multiplier strip voltage obtained by adjusting the grid voltage at each strip potential for maximum gain. Figures 6 and 7 show that the maximum gain of tube number 610F was almost identical to that of tube 607A; when the angle the latters multiplier strip made with the tube axis was 20°. The maximum gain of both devices occurred at the same overall voltage, approximately 1400 volts. No further increase of gain was obtained by increasing the strip voltage and in fact, increasing the voltage caused a decrease in gain. The precise reason for this fall was not determined. Distortion of the electric field which was maintained by relatively remote electrodes or temporary loss of minute quantities of cesium due to joule heating of the strip are feasible causes.

Figure 8 is a schematic diagram of tube Serial No. 620F. The major design feature of this tube was the multiple grid structure surrounding the strip. The test results of this tube, again show the dependence of gain on electric field shaping by the grids. The low gain of this tube was attributed to the poor secondary emissive characteristics of the particular strip. Further consideration of this, subsequent field plots and bell jar experiments indicated, that with the strip mounted at 19.5° with respect to the equipotential lines, the desired field configuration would be achieved.

The measured grid currents did not show a definite increase with the decrease of gain which indicates that there was no excessive collection of secondary electrons by the grid and that the shape and strength of the electric field were the major factors determining the gain of the tube. The resulting gain curves are shown in Figure 9 .

One tube was made employing a silicon resistive strip. This tube was not tested due to the 80% decrease in multiplier strip resistance caused by tube processing. Other silicon resistive films, exposed to standard tube processing in glass enclosures, exhibited stable characteristics at up to 3.5 kilovolts.

The overall test data of strip multiplier tubes clearly indicated the need for detailed investigation of the electric field configuration and its effect on the performance of the multiplier strip.

The tests also showed the necessity for further evaluation of resistive strip materials.

6. PARALLEL FIELD EXPERIMENTS

To confirm the test results of strip multiplier tubes an experiment was designed to evaluate the performance of the multiplier strip in a practically distortion-free parallel electric field. Figure 10 shows a schematic of the electron gun and the multiplier strip assembly used in the experiment.

The information obtained from this experiment consisted of:

1. Multiplier strip gain characteristics, as a function of voltage, and angle of inclination,
2. electrical and physical properties of strip materials,
3. the potentials necessary for attaining practical gains from the multiplier strip,
4. the effect of electric fields on the gain of strip electron multipliers; and
5. confirmation of suspected electron loss to the field shaping electrodes.

The greatest gain was obtained with a 700 megohm silicon film on a glass substrate. Gain vs. applied voltage curves are shown in Figures' 11 and 12. Figure 11 shows gain vs. strip multiplier voltage at five different angles α of strip inclination with the vertical axis. A gain of 148,000 was obtained when the angle of the strip made with the vertical axis was 20° ± 1°. This gain was obtained with the strip potential of 3750 volts, which was the maximum potential used in this experiment.

The curves indicate that much higher voltages were needed to get the required gain. Since the resistance temperature coefficient of silicon, as shown in Figure 14, is negative the power dissipation of the strip had to be kept below 50 milliwatts in order to prevent progressive decrease in strip resistance and ultimate breakdown. Figure 14 shows the published [1, 2, 3] resistance temperature curves for bulk silicon and also those for evaporated silicon films made under this program.

Silicon film strips with resistance of 750 megohms were successfully made. These strips were operated satisfactorily, at room temperature, with an overall potential of 4000 volts.

As shown by the curves of gain versus angle (Figure 12) the gain of the multiplier strip increased as the angle was approaching 20°. As soon as the angle became larger than 20°, a sharp drop in gain occurred.

As stated in section 3 of this report, the maximum gain of Tube No. 1 was obtained with the strip angle at 4° with respect to tube axis. However, this occurred when the grid electrode potential was close to that of the negative end of the strip. Even when the grid was disconnected, this was so, because of the high conductive path between negative end of the strip and the grids. Therefore, in each case the field shape would have been similar to that sketched in Figure 13, which shows that the angle of the strip made with the normal to the field was approximately 20°.

The angle for maximum secondary yield in a practically perfect parallel electric field for a constant energy of primary electrons appears to be about 20°.

This agrees substantially with the assumptions made in the theoretical calculations.

No significant gains were obtained from magnesium oxide coated silicon and gallium arsenide resistive strips; however, Figures 15 and 16 do show that the 20° angle of the multiplier strips yielded highest gains.

The low gain of both strips might be attributed to low secondary yield of magnesium oxide due to possible contamination of the oxide layer.

No gain was obtained with a plain gallium arsenide resistive strip.

In order to substantiate the suspected loss of electrons from the edge of the strip to the grids, gains of one inch and 1/2 inch portions of the same multiplier strip were measured. If there was no loss of electrons to the field shaping grids with the voltage gradient the same in each case, the gain of the one inch long strip would have been equal to the square of the gain of the one-half inch long strip. However, the gain of the longer strip was only double (1730 compared with 860) that of the shorter strip.

Additional confirmation, that secondary electrons were being collected by the field shaping electrodes, was obtained by operating the 1" long and the 1/2 inch long strips at the same overall voltage. Under these conditions the gain of the shorter strip was greater than that of the longer. (800 compared with 456). If there was no loss of electrons to the field shaping grids the gain would have been the same in each case.

The loss of secondary electrons to the grids can be attributed to their initial energy distribution and their direction of emission from the multiplier surface. These factors result in the spreading of the cascading "beam" of electrons as it progresses along the multiplier strip. When the spreading electron "beam" becomes as wide as the strip itself a certain proportion of the electrons emitted from points near the edge follow trajectories which terminate on the surfaces of the field shaping electrodes. To some extent this loss can be eliminated by using a "bell" shaped field; however, if the multiplier strip has to be long in order to get the required gain, the multiplicity of electrodes necessary to provide the "bell" shaped field would eliminate the advantages of the strip multipliers simplicity.

A second solution would be to widen the multiplier strip and provide the multiplicity of electrodes, with which to maintain a parallel electric field within an operational device. Again, the complexity and size of a strip multiplier made to give the required gain would be greater than that of conventional multiplication devices.

The peak gain of the strip in the "bell" shaped field was higher than that obtained with 1/2 and one inch strips, at the same voltage, in the parallel field indicating smaller loss of electrons to the grid in the "bell" shaped field.

7. CONCLUSIONS

The feasibility of making a strip electron multiplier was demonstrated. However, it is evident that serious limitations do exist which prevent the manufacture of a small, high gain strip multiplier which can handle relatively high input currents. For example, the light flux from the Star Canopus, focussed into a 10^{-8} lumen spot, impinging on a 40 microampere per lumen photocathode would produce an input current of 4×10^{-13} amperes and if the strip gain is 10^{6}, an output current of 4×10^{-7} amperes.

A small device with a simple electrode configuration was made. The maximum gain of this, with the electrode potentials adjusted to give a "bell" shaped field was in the order of 10^{5}. The feasibility of the approach was demonstrated further during the parallel field experiments, however, it was found that material limitations do not allow the construction of a small device which will have sufficient gain and current output capability. The same limitations will apply equally to single channel and multichannel tubular electron multipliers based on similar theoretical approaches.

It is concluded that a strip multiplier could be made to perform the functions of the conventional, focussed type electron multiplier, now being used in the Canopus star tracking system image dissectors. However, a practical device which would fulfill these functions would in all probability be larger and more complex than the conventional multipliers presently used. For these reasons it is recommended that further effort be directed towards the design and development of miniaturized electron multipliers using conventional secondary emissive surfaces and electrodes.

8. REFERENCES

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2. G. L. Pearson and W. H. Brattain, "History of Semiconductor Research", Proc. IRE, 43, 1794 - 1806, Dec., 1955

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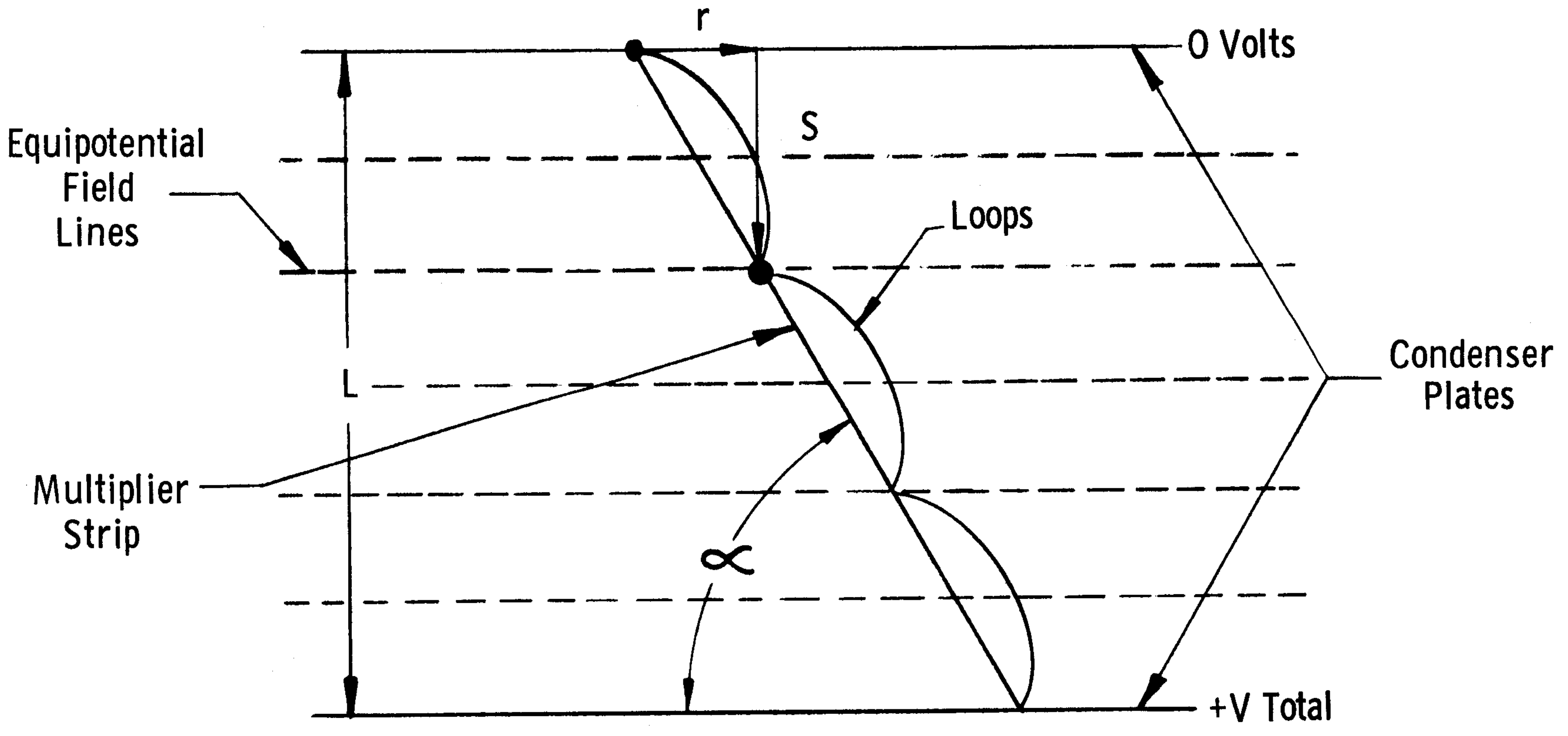
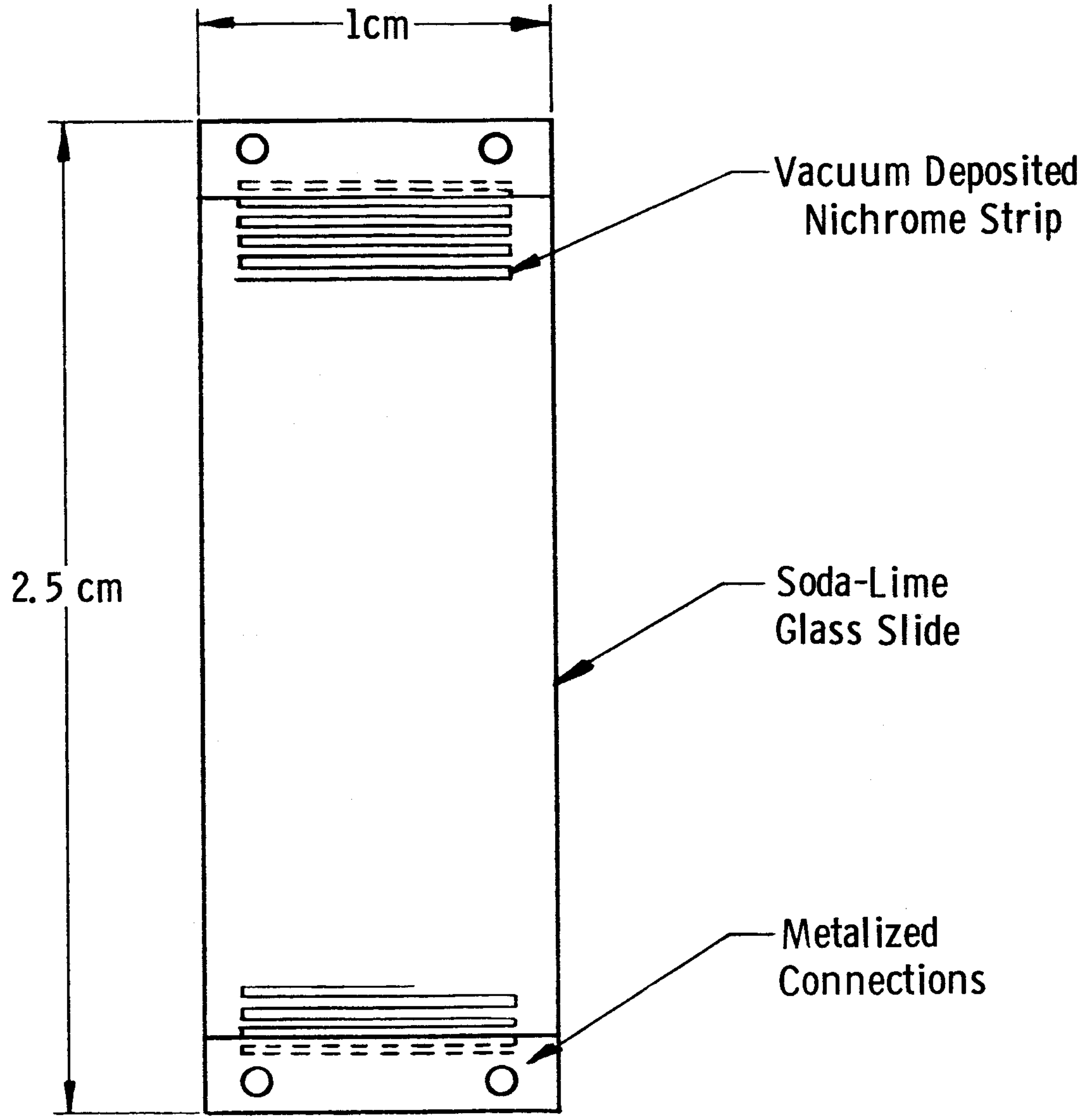


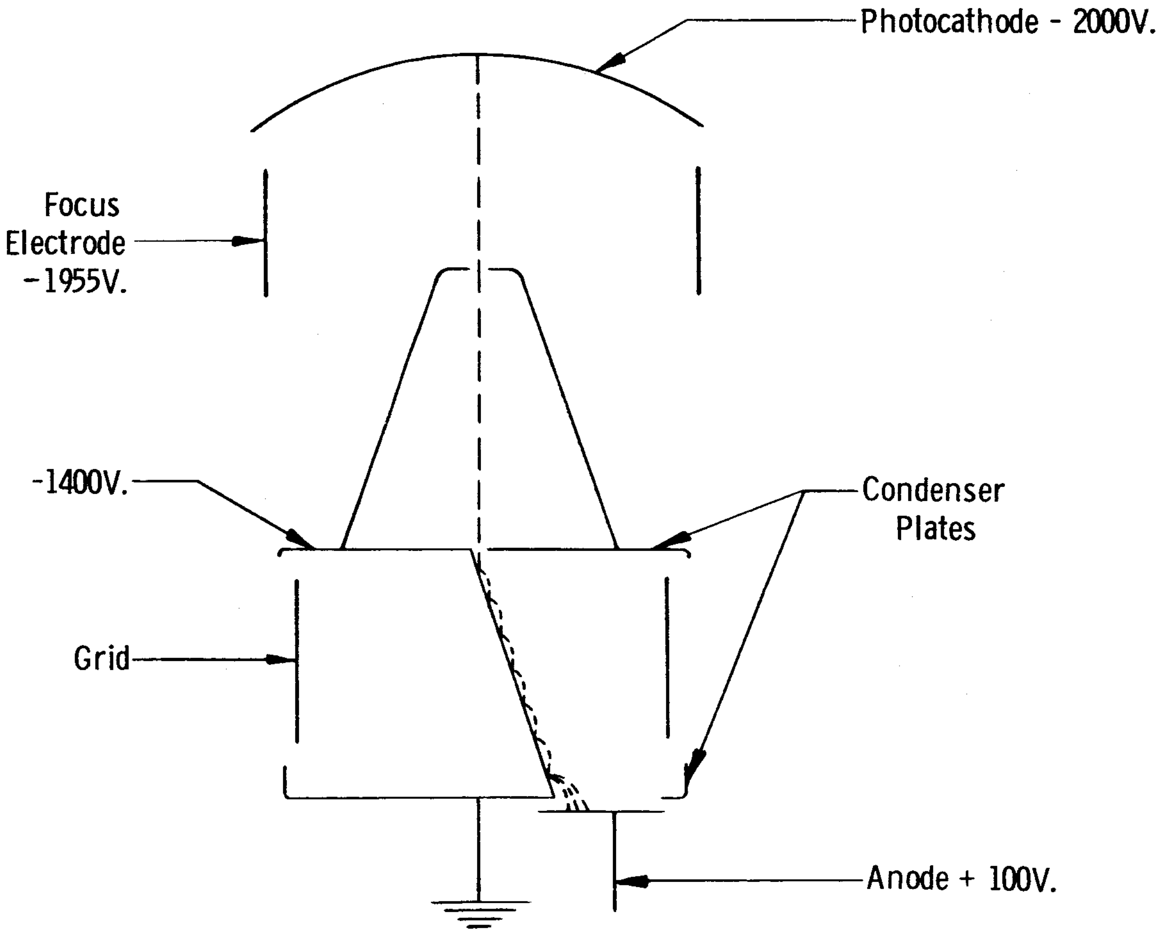
Multiplier Strip in Parallel Electric Field.

Figure 1



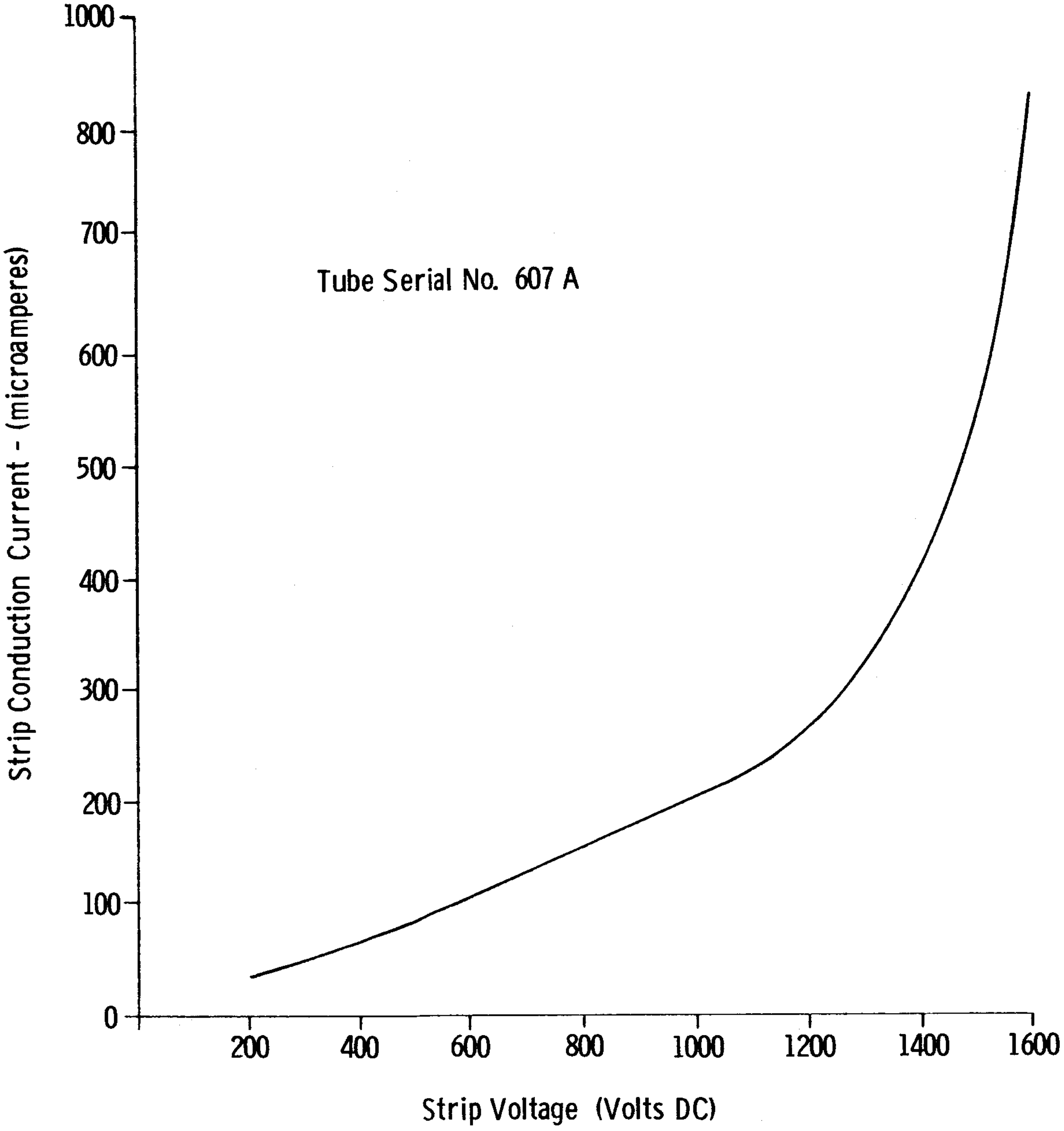
Design of Ladder Type Nichrome Film Multiplier Strip

Figure 2



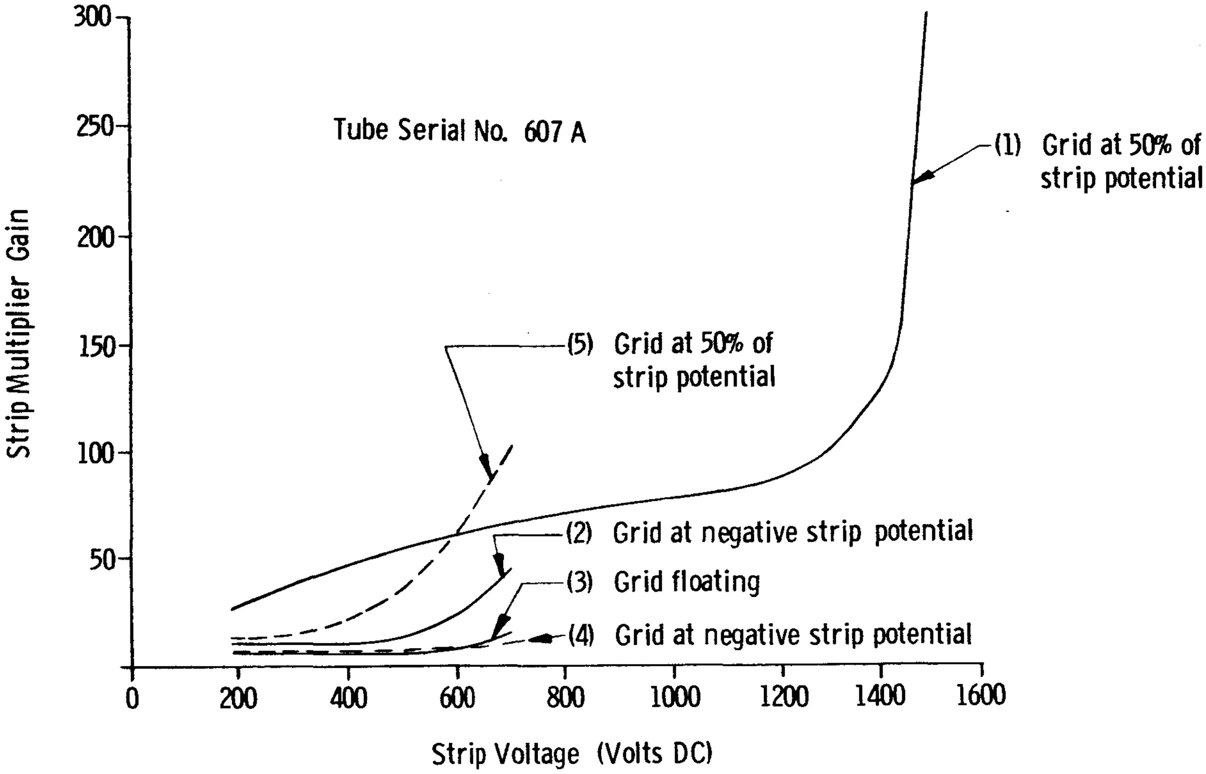
Schematic of Experimental
Strip Multiplier Tube

Figure 3



Effective Strip Conduction Current vs. Applied Voltage
(First Experimental Strip Multiplier)

Figure 4



Test Conditions

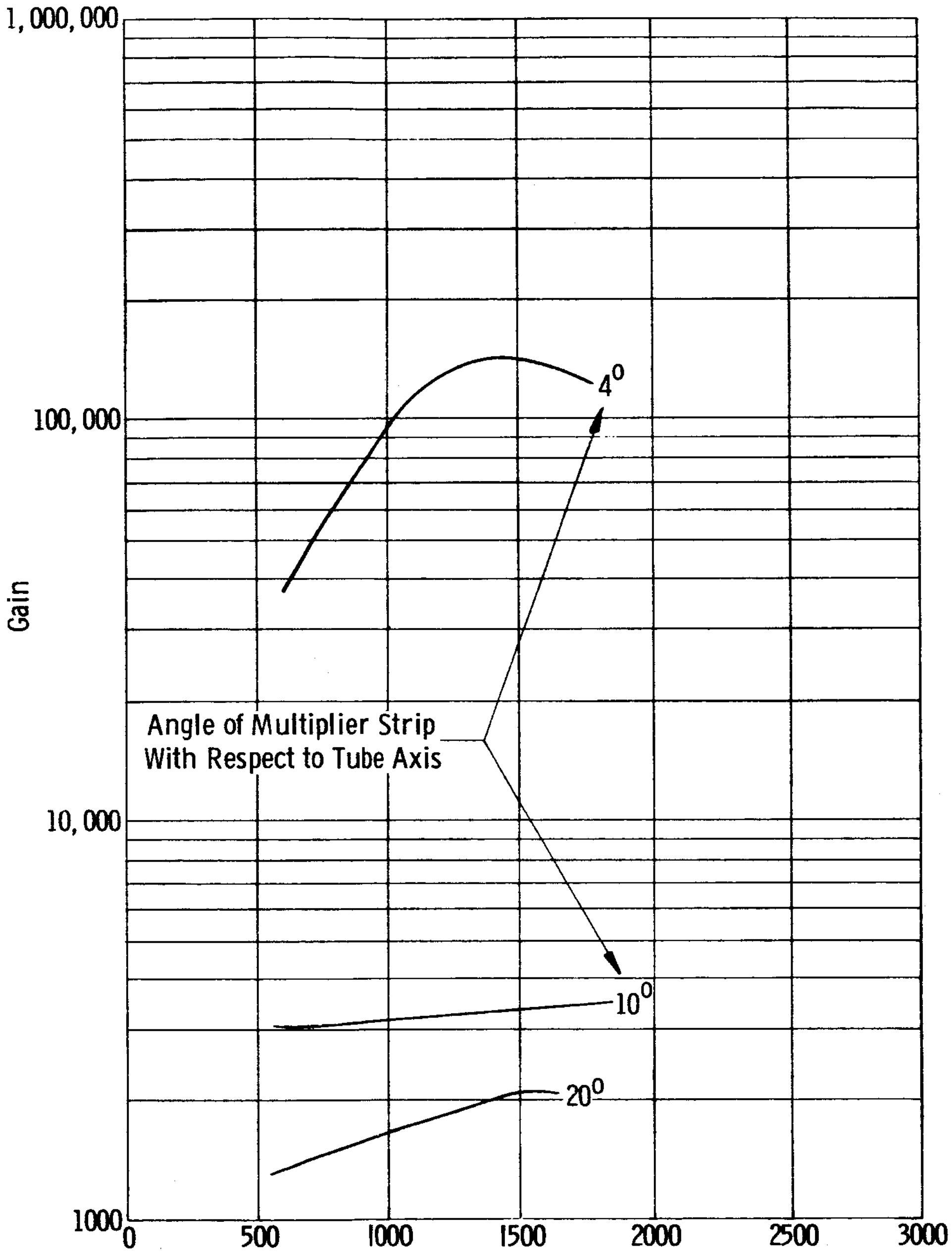
1. General
   Image section voltage = 500 Volts
   Focus electrode voltage = 50 Volts with respect
   to photocathode
   Collector voltage = 90 Volts with respect to the
   bottom of the strip

2. Curves 1, 2, and 3
   Strip resistance = $7x10^6$ ohms
   Leakage resistance (Bottom of strip to grid) = $6x10^6$ ohms
   Leakage resistance (Top of strip to grid) = $2x10^5$ ohms
   Strip angle = 15° with the vertical

3. Curves 4 and 5
   Strip resistance = $8x10^6$ ohms
   Leakage resistance (Bottom of strip to grid) = $6x10^6$ ohm
   Leakage resistance (Top of strip to grid) = $1x10^6$ ohms
   Strip angle = 25° with the vertical

Strip Multiplier Gain vs. Applied Voltage
(First Experimental Strip Multiplier)

Figure 5

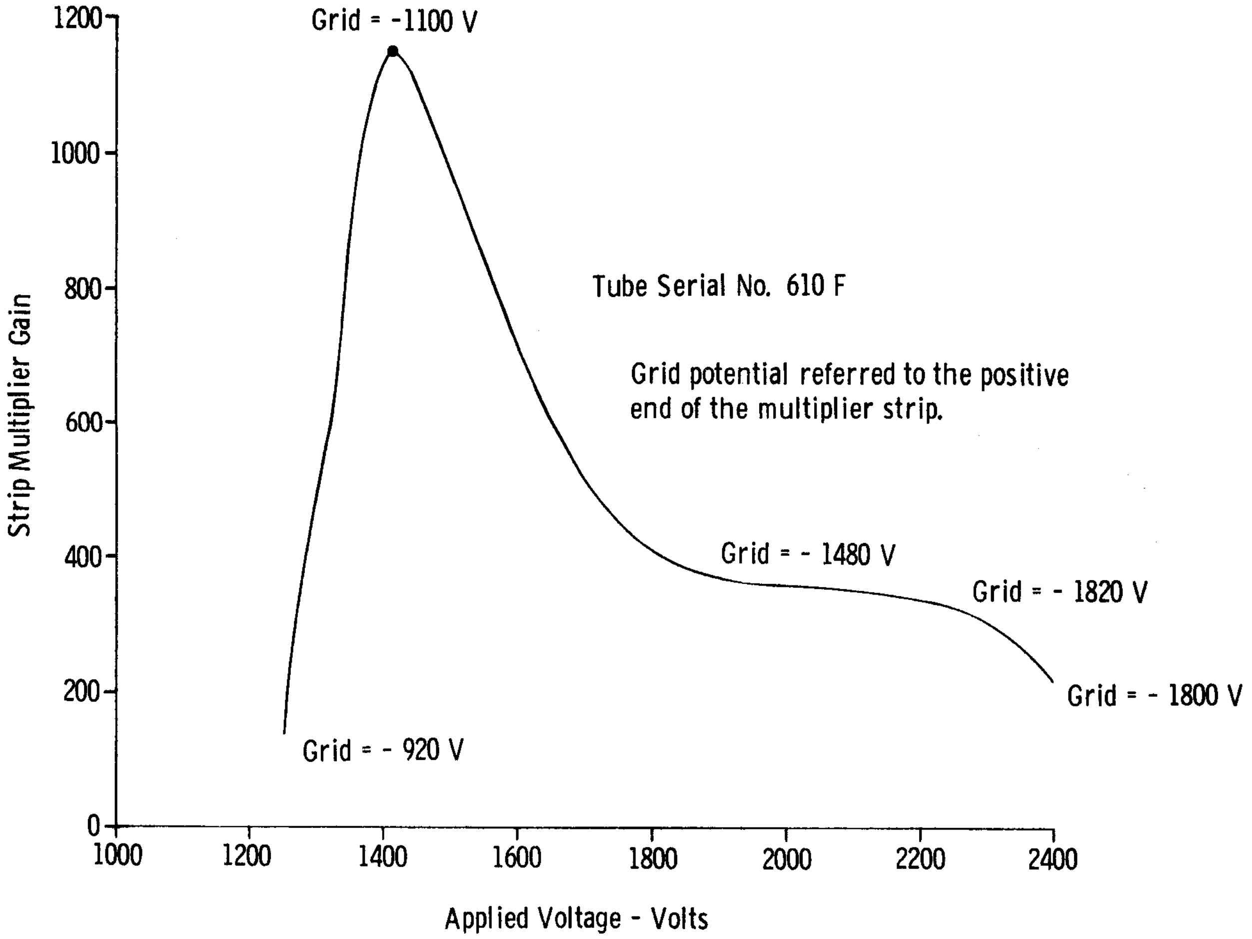


Applied Voltage-Volts

Multiplier Gain vs. Applied Voltage
(First Experimental Strip Multiplier)

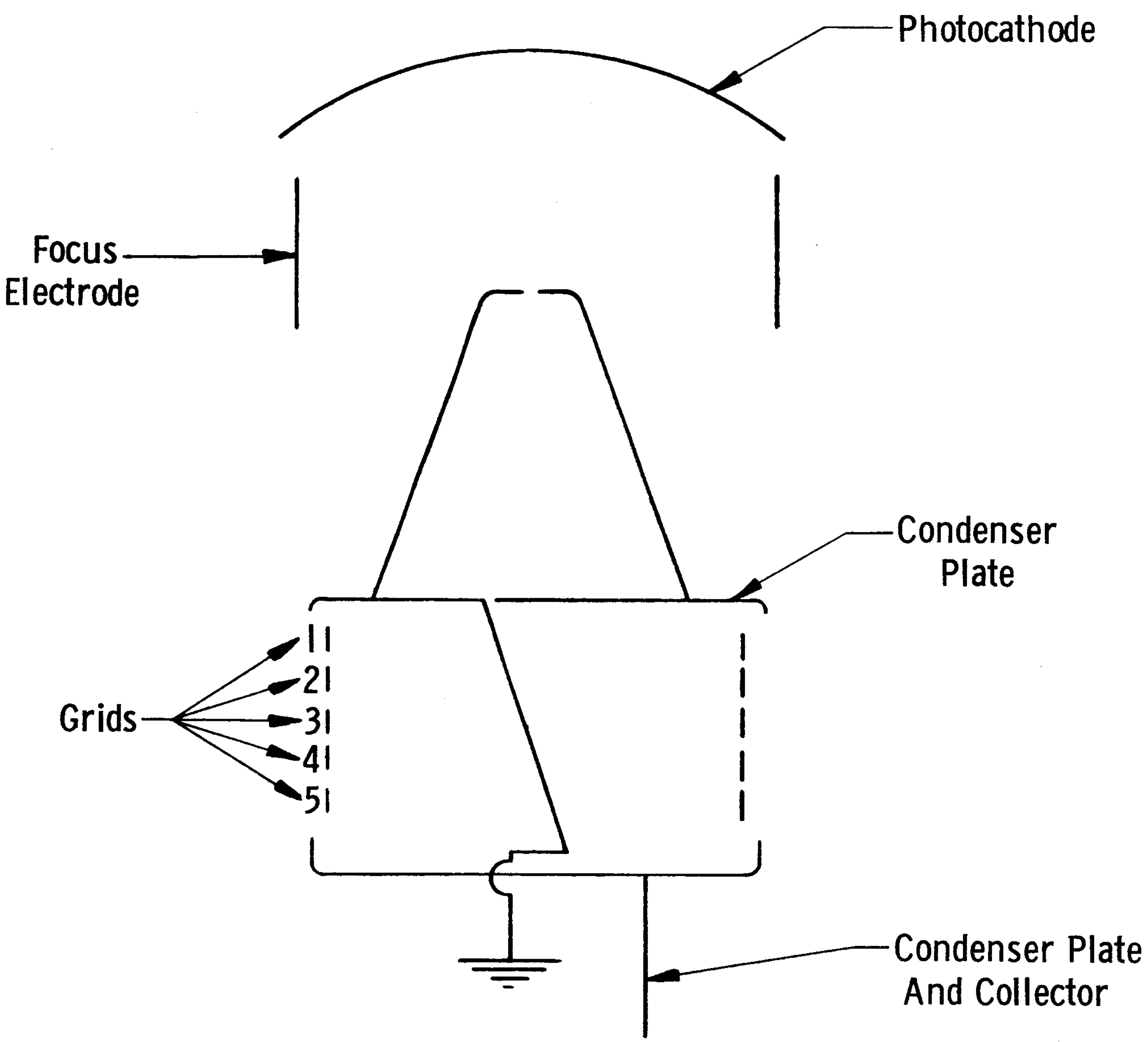
Tube Serial No. 607 A

Figure 6



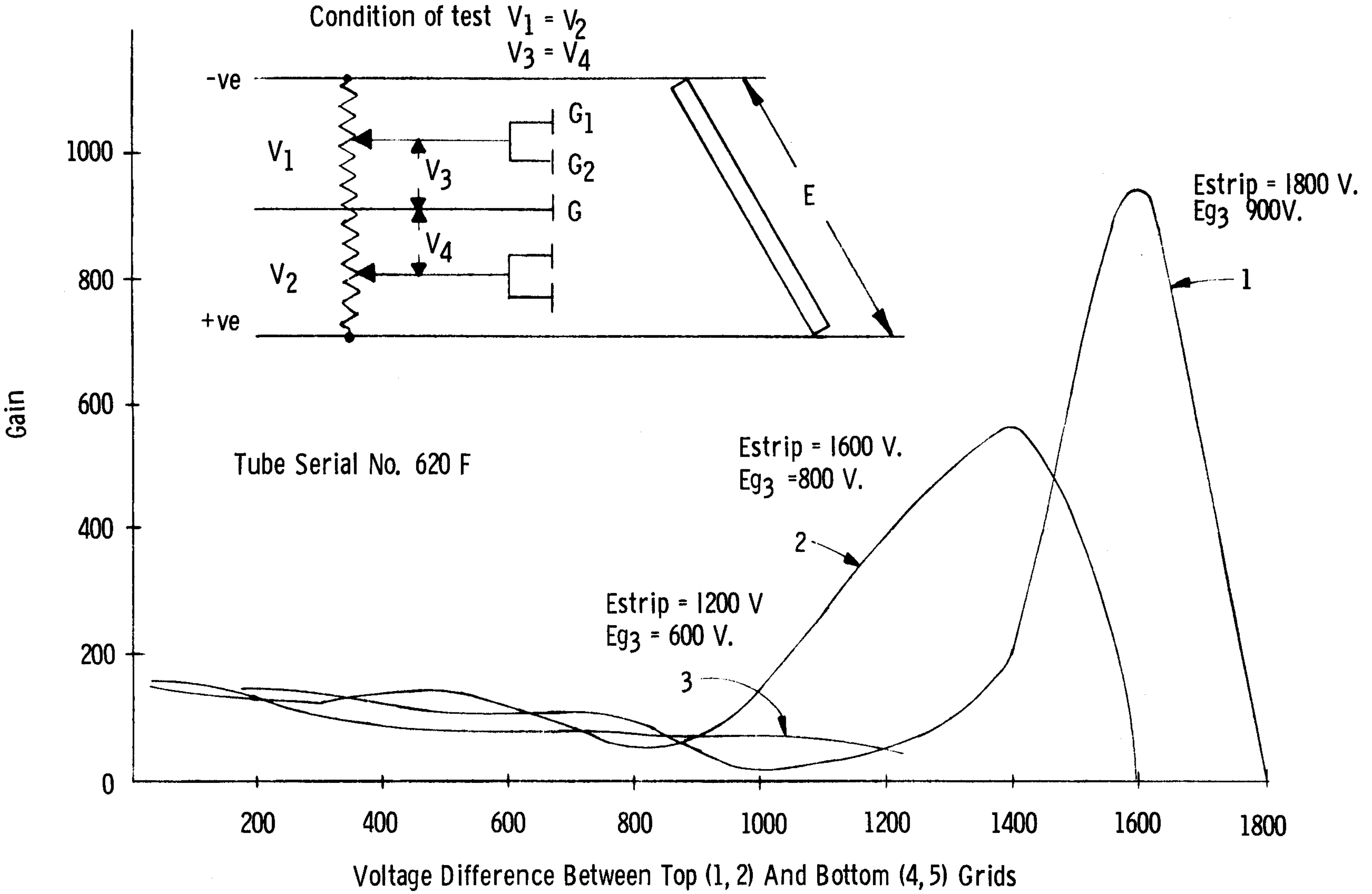
Strip Mutliplier Gain vs. Applied Voltage
Grid Potential Adjusted For Maximum Gain
(Second Experimental Strip Multiplier)

Figure 7



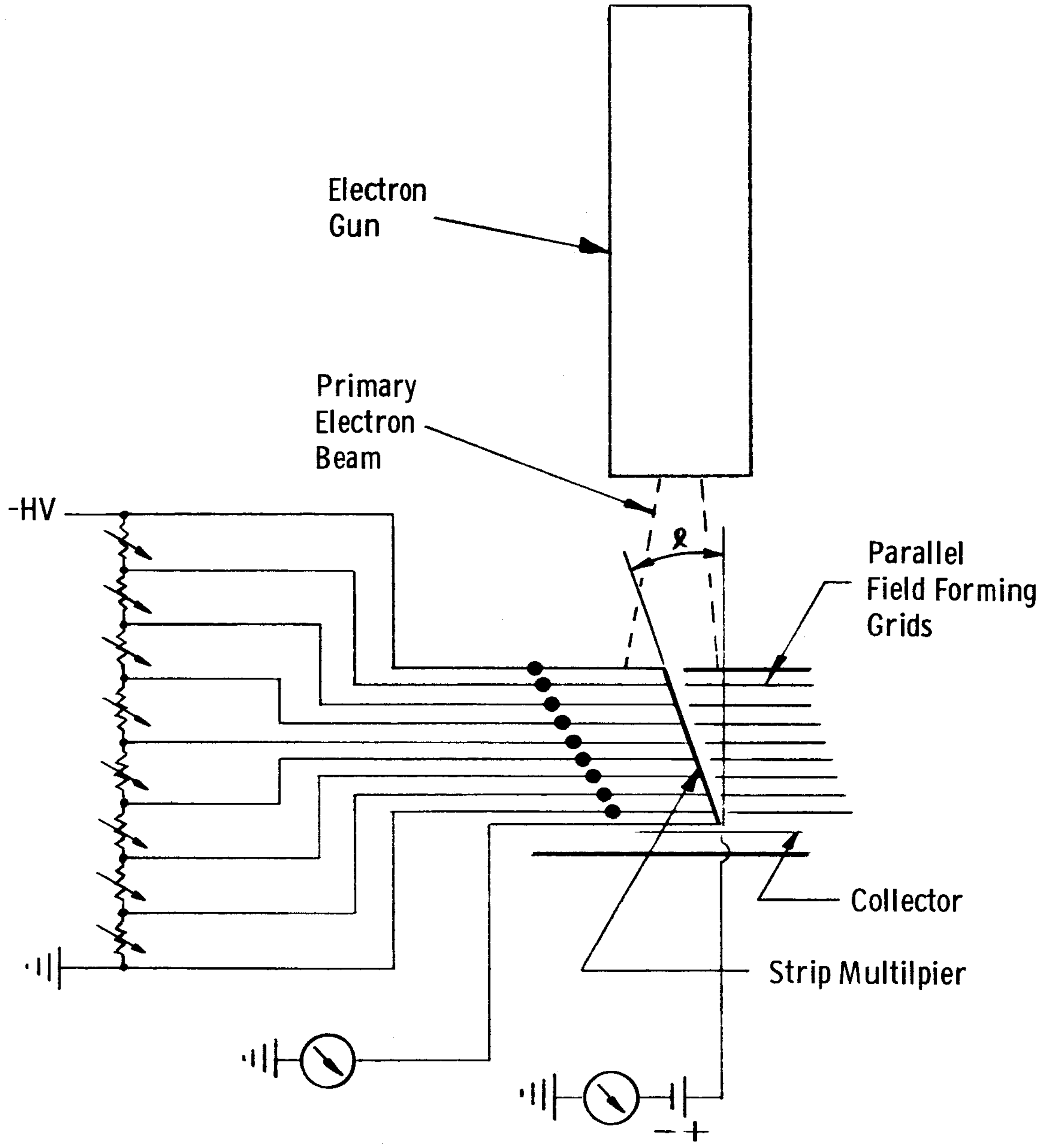
Schematic of Experimental
Strip Multiplier Tube

Figure 8



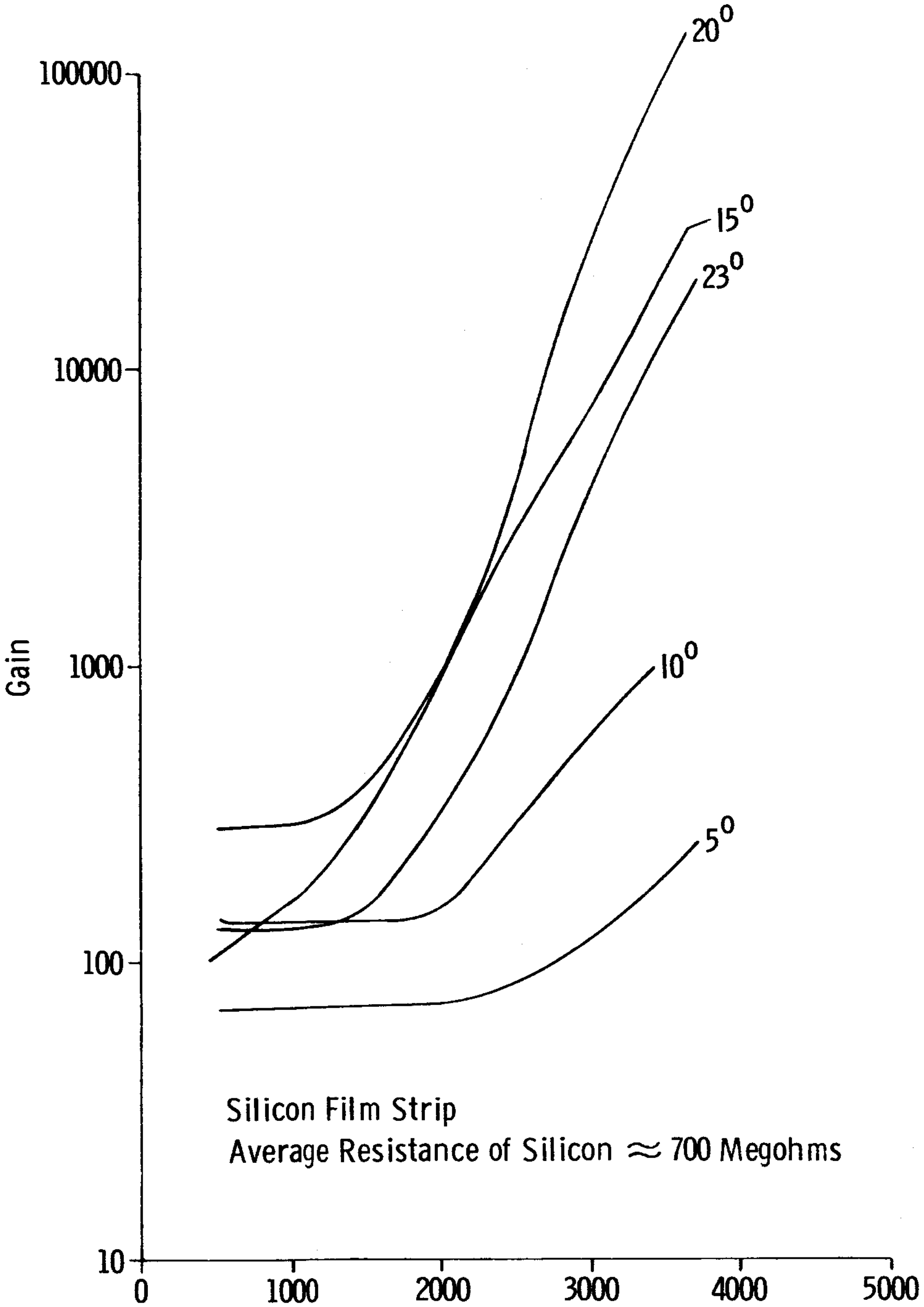
Electron Multiplier Gain
(Multiple Grid Design)

Figure 9



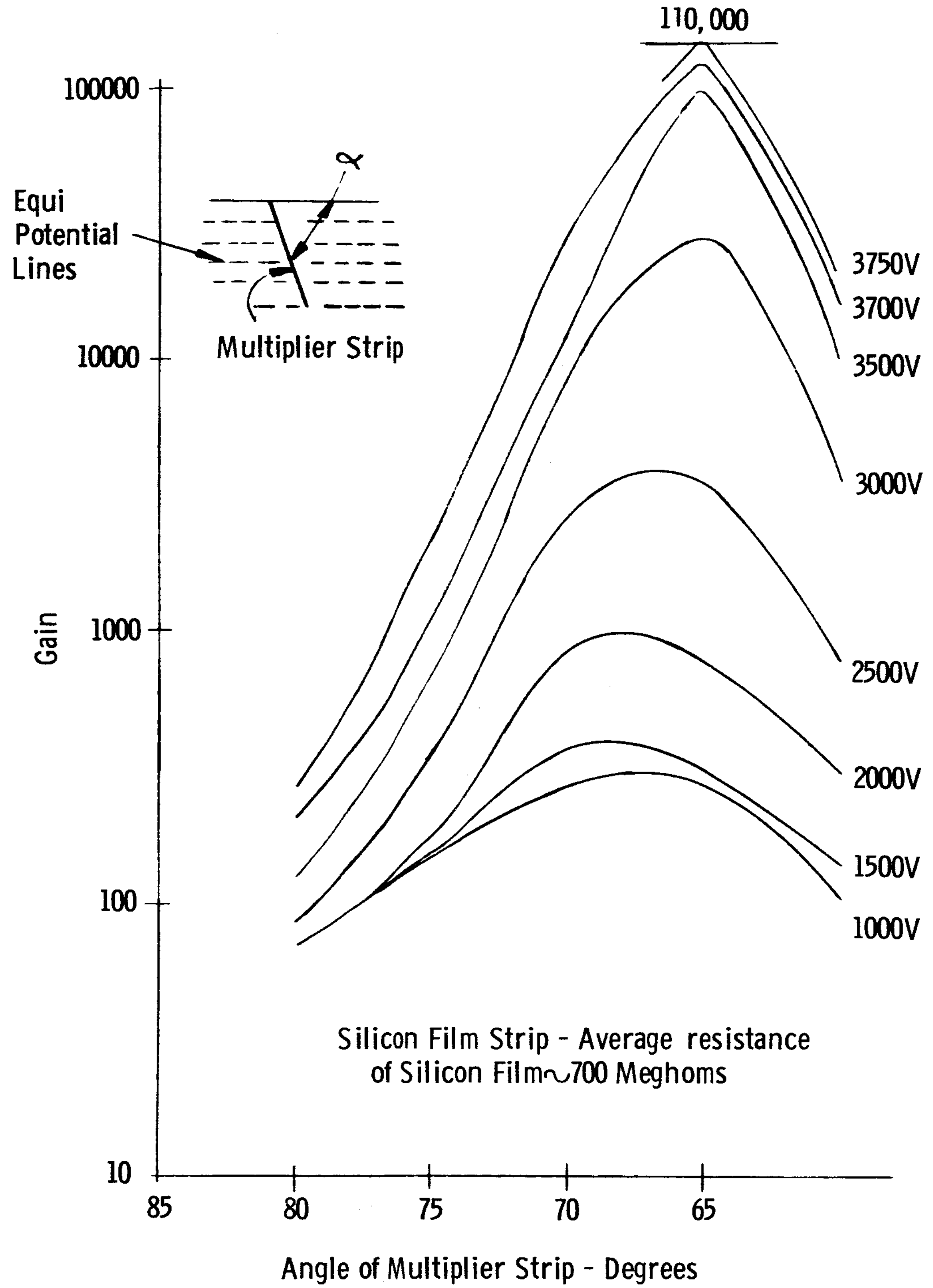
Shematic Of Parallel Electronic Field Experiment

Figure 10



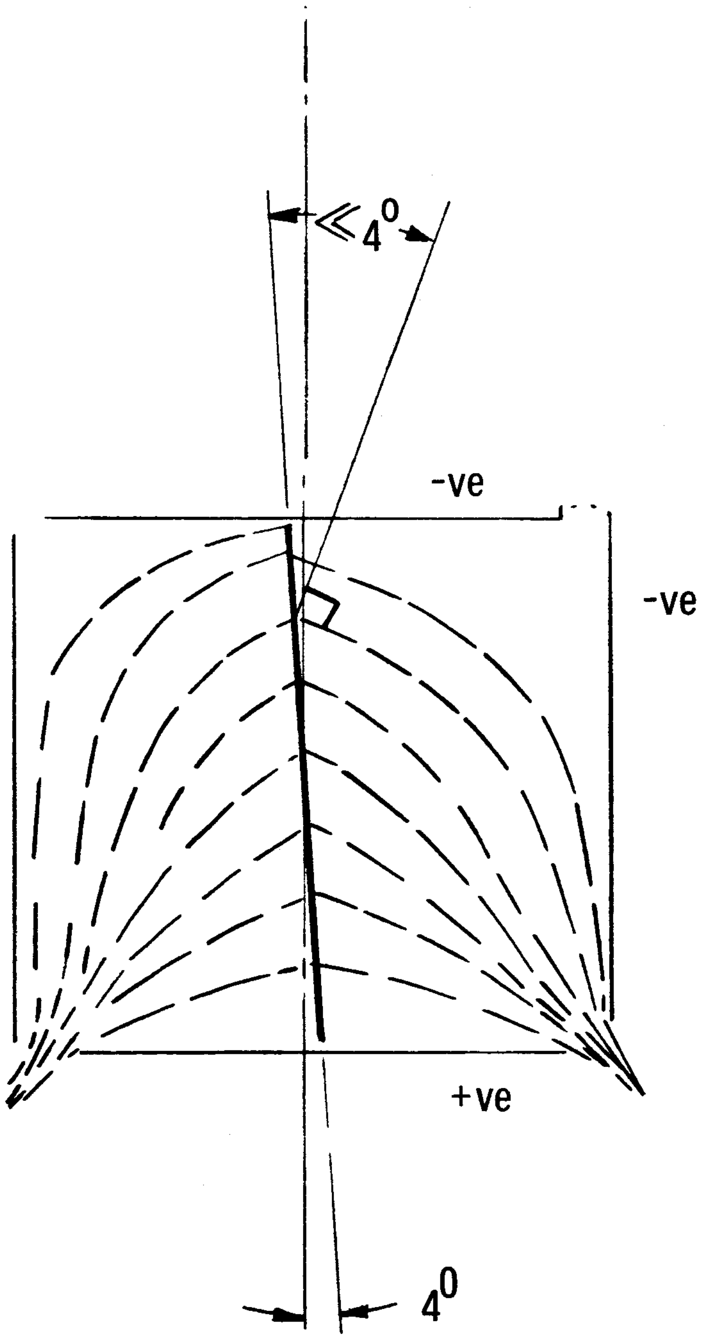
Multiplier Strip Gain Vs. Applied Voltage

Figure 11

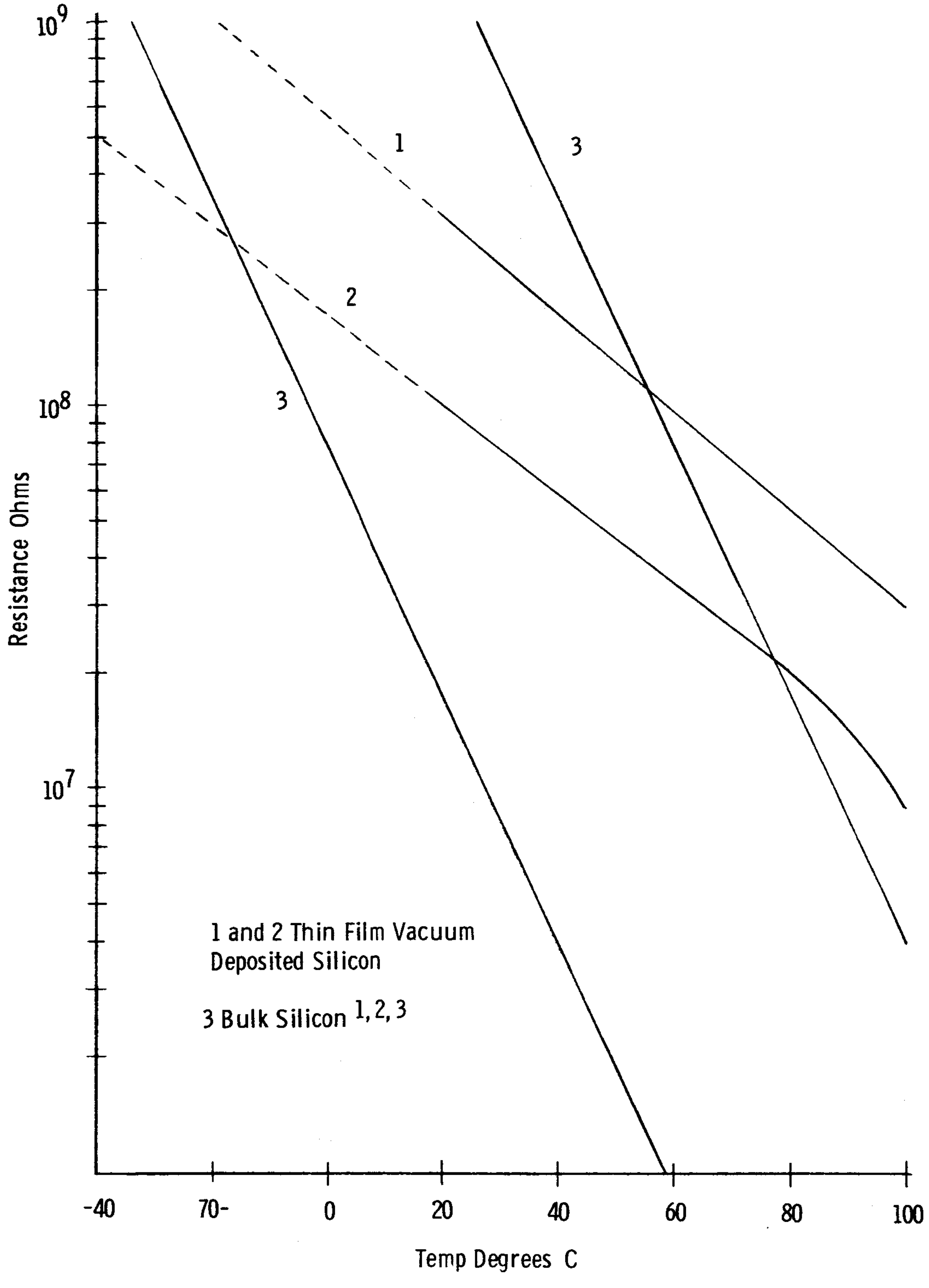


Multiplier Strip Gain vs. Angle of Strip

Figure 12



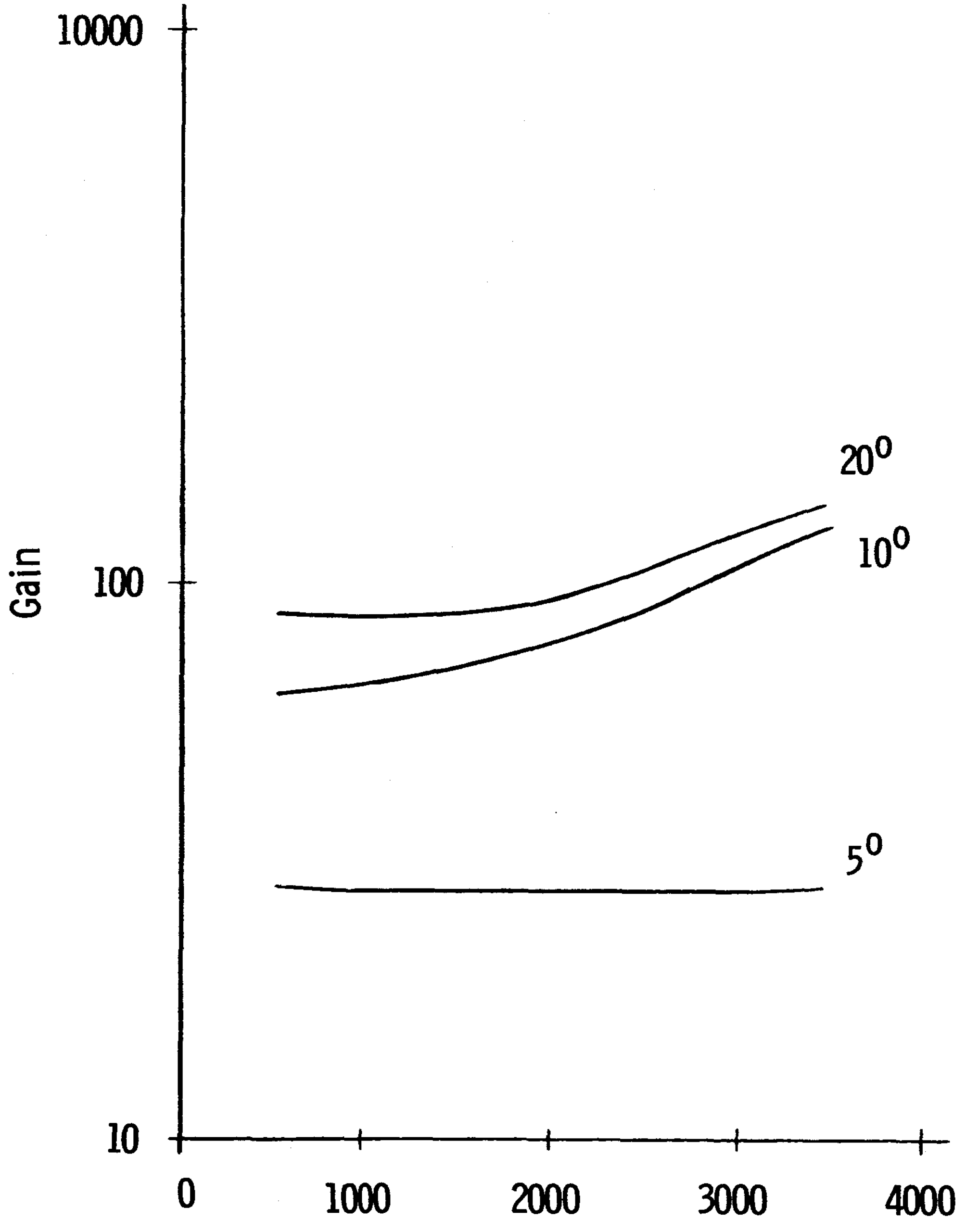
Electric Field Shape in Experimental Device
Figure 13



Silicon
Temperature/Resistance Characteristics

Figure 14

Silicon Film Strip With Magnesium Oxide Coating

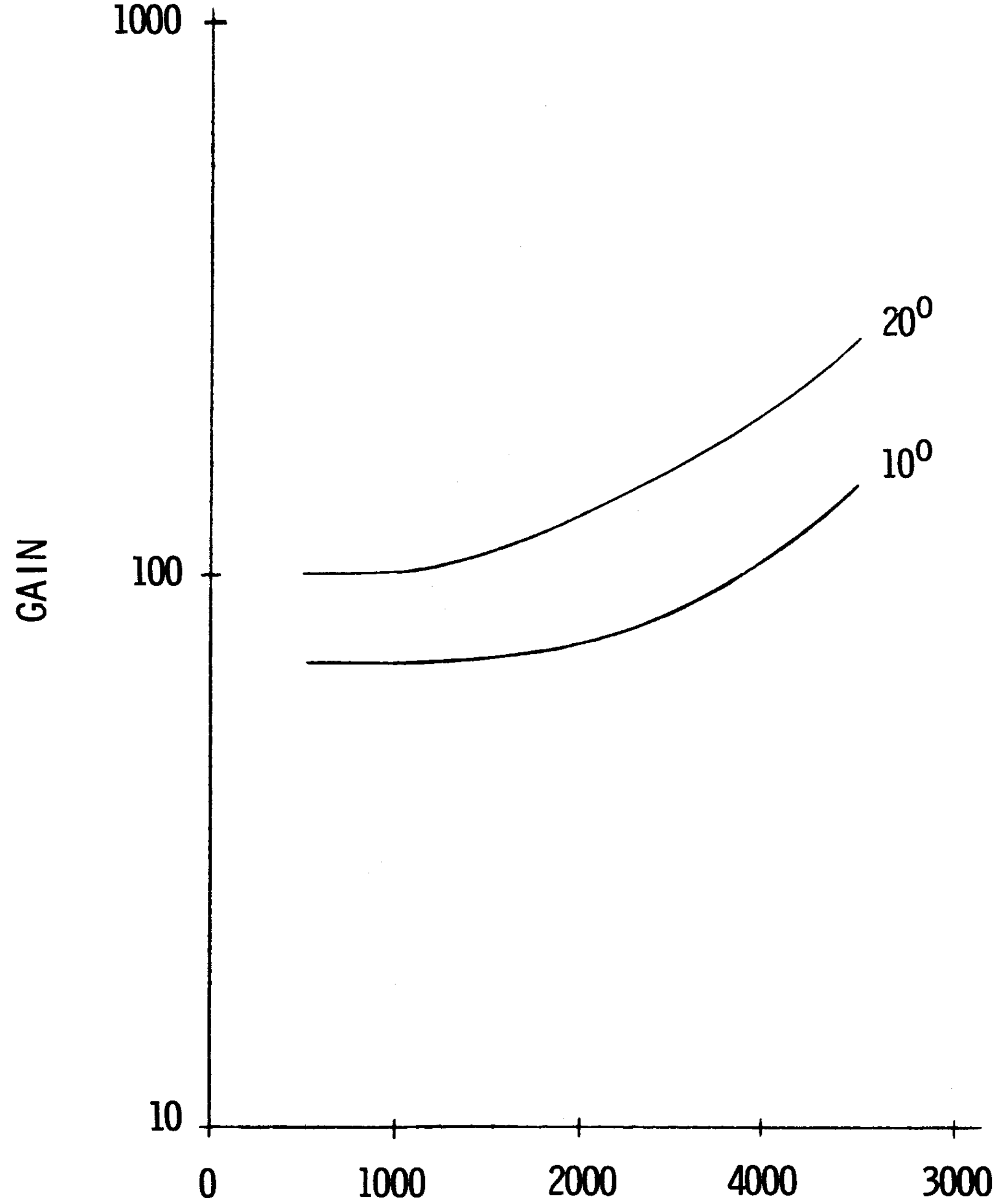


Multiplier Strip Gain vs. Applied Voltage

Figure 15

Magnesium Oxide Coated Gallium Arsenide Strip

Average resistance ~500 Megohms



Strip Multiplier Voltage - Volts

Multiplier Strip Gain vs. Applied Voltage

Figure 16