I. MICROWAVE AND PHYSICAL ELECTRONICS

A. Construction of 5 mm. Oxford Type Tube

Staff: Mr. N. G. Parke

Description of Project and Plan of Action.

The purpose of this project is to construct the scaled down version of the 2K-33 tube which was designed by G. H. Vineyard, January 4, 1946. This tube differs from the 2K-33 in the following features:

1. Electron gun not scaled down.
2. Hole through which the beam passes scaled down by a factor .5 and not .4.
3. Outer cavity length $\lambda/4$ instead of $3\lambda/4$.
4. Glass removed from outer cavity and placed as a window in the output wave guide.

This project has been divided into three stages:

Stage 1. Manufacture and attempt to assemble parts for three tubes based on Vineyard's original sketches. If one is successfully assembled, test it for ratio of cathode current to reflector current, i.e., accuracy of gun allignment and focus.

Stage 2. Engineer a set of shop drawings covering small parts, assembly, tuner, and tooling. These drawings to incorporate the techniques of construction developed in stage 1.

Stage 3. The manufacture and assembly of sufficient tubes based on drawings made in stage 2 to prove the success or failure of the basic design and if successful to obtain representative data on the operating characteristics.

Progress.

Stages 1 and 2 are essentially completed. Two of the three prototypes have been successfully assembled. A preliminary test shows reasonable gun allignment and focus, i.e., a .66 ratio of cathode to reflector current. Pending a small modification in the test equipment, the two prototypes will be tested for ability to oscillate and output. The parts for stage 3 are in process of manufacture.

I. B. High Power S-Band Magnetron

Staff: Professor S. T. Martin
Mr. J. Henry

A single tube utilizing a rising sun anode and a waveguide output is under construction. As reported earlier the essential features are scaled up from a successful 1 MW 3 cm. tube designed by the Columbia Radiation Laboratory.

At the present time fabrication problems caused by the larger than ordinary sizes of parts are causing major delays. An r-f window of 707

glass measuring 3 1/4" diameter has been made successfully for the waveguide output.

It is estimated that this tube will be completed for testing by August 1, 1946. A serious shortage of large sizes of OFHC copper threatens to hold up manufacture of any further tubes until after January 1, 1947.

I. C. Magnetron Theory Research

Staff: Dr. G. I. Harrison

The problem of the behavior of a magnetron consisting of a plane cathode, plane anode, d-c voltage between cathode and anode, d-c magnetic field parallel to the cathode and anode surfaces, and r-f voltage superposed on the d-c voltage between cathode and anode is being treated theoretically. The case where the magnetic field is greater than the cutoff value has been considered, so that no d-c current flows between the electrodes. The problem that has been considered is the r-f current resulting from the impressed r-f voltage, and the resulting r-f impedance or admittance. Since no electrons actually reach the anode, it is clear that the r-f current is of the nature of displacement current, in the region near the anode.

The interest in this problem is two-fold. In the first place, it forms one of the simplest examples of r-f magnetron action, and a careful study of its theory, coupled eventually with an experimental study of a comparable case, should be valuable in comparing magnetron theory with experiment, which has been very inadequately done up to the present. Experimental checks could be made on a cylindrical magnetron, which would not be very different from the linear magnetron for which the calculations are being carried out. The second reason for interest is more practical. The magnetron of the type described forms an r-f load, with resistance and reactance. The impedance depends on the electrical parameters of the circuit, and hence can be varied electrically. Such a device could thus be used as an electrically tuned reactor, and could be attached to a resonant cavity, as a magnetron cavity, so as to tune it electrically. Various types of electronic tuning for magnetrons have already been used, some based on a principle similar to that considered here, and study of the parallel plate magnetron seems like a first step toward understanding the theory of electronic reactors of the magnetron type, which has hardly been touched up to the present.

The calculation has so far been only a first approximation, in which the effect of the space charge on the field acting on the electrons has been neglected, the assumed electric field being independent of position, though varying sinusoidally with time. Under these circumstances the motion of an individual electron can be calculated analytically, so that at first sight the problem of finding the r-f current would seem to be trivial. The reason why it is not, is that electrons leaving the cathode in certain phases return to the cathode after one period, while in other phases they may not return for many periods. The problem is then to find how many electrons will

still be in the interaction space at any phase, taking account of those which strike the cathode and are presumably lost to the discharge. It is assumed that electrons are emitted from the cathode at a uniform rate. A further refinement, which has not been carried through, would take account of the fact that the rate of emission would really have to vary over a period of the r-f field, in order to be consistent with an instantaneous space charge limitation.

Subject to the approximations above, the calculation has been carried through, partly numerically and partly analytically, in such a way that the r-f current as a function of r-f voltage is known, as a function of frequency, for at least certain r-f voltages, and ranges of d-c parameters. There is a resonance at the Larmor frequency, the resistive component rising to a maximum at this frequency, and the reactive component going through zero, the Q of the resonance being small, of the order of magnitude of 10. The r-f current is not proportional to the r-f voltage though it is linearly related to the r-f voltage for small r-f voltages. Thus there appears to be a non-vanishing r-f current for vanishingly small r-f voltages which results in a discontinuous on-off effect. The main part of the calculation has been completed and written up. Pending completion of the theory, no experimental check has been started.

I. D. Cathode Research

Staff: Dr. A. S. Eisenstein
Mr. J. R. Dillinger
Mr. W. E. Mutter

1. Cathode Coating Composition

The standard x-ray diffraction method of measuring the BaO-SrO composition ratio in oxide cathode coatings from determinations of crystal lattice constants is subject to possible errors of $\pm$ 2 to 5 %. This is particularly serious in correlations of emission vs. composition toward the "end of life" when the coating becomes largely SrO. It is proposed that techniques be improved to permit $\pm$ errors of about $\frac{1}{2}$ % by obtaining an accurate plot of composition vs. lattice constant. Mr. E. B. Read at M.I.T. has been able to separate Ba and Sr in coating samples, using a chromate precipitation method, and to obtain their ratio to within $\frac{1}{2}$ %. Back reflection x-ray techniques permit a determination of lattice constant to 0.0005 Å or a composition accuracy of 0.1 %.

2. Thin Film Emission

The thermionic emission properties of thin evaporated films of BaO and Ba on pure Ni are being studied as a function of the film thickness and temperature. Two significant differences appear in the behavior of these materials at a given temperature (1) the emission from BaO passes through a definite maxima as the film thickness increases whereas the emission from Ba approaches an equilibrium value, and (2) the

rate of emission decay, when the evaporation ceases, is considerably more rapid in the case of Ba than BaO.

To within the accuracy of measurement of about 10 %, the d-c and 1 μS pulsed emission current-voltage characteristics of Ba films are identical. Similar results are indicated in tests on standard weight oxide cathodes at a temperature of about 550° C. The major obstacle in extending such correlations to higher temperatures appears to be the effect of anode contaminants under d-c operation.

In one evaporation experiment performed in an electron diffraction chamber an appreciable thermionic emission was obtained from a film of Ba on pure Ni before the film thickness was sufficient to give rise to diffraction lines. The film thickness must certainly have been less than 10 atomic layers.

3. Oxide Cathode Interface and Coating Resistances as Measured by Embedded Probes

A technique for measuring interface and coating resistances was advanced by the Bartol Research Foundation[1] and the Radiation Laboratory[2]. According to this method a length of about 8 mm. of a cylindrical cathode 3 mm. in diameter and 14 mm. long is sprayed with appropriate alkaline earth carbonates. A .0005" diameter wire is wound helically around this layer of coating. Another layer of coating is sprayed on; another wire is wound on; and then a top layer of coating is sprayed on. In testing these tubes the peak pulse current and the potential of each probe are measured. From these data and the measured weight of coating between the two probes the coating resistance can be determined. By subtracting an amount equal to the resistance of the known weight of coating between the base metal and the first probe from the measured resistance between the base metal and first probe, the "interface resistance" can be determined. Measurements obtained in this way have been used to justify the following model for an oxide cathode: base metal + blocking layer + excess semi-conductor + surface (See R. L. Report 933).

The program of work for the past 6 months period consisted of the following 3 parts: (1) To investigate the reliability of probe voltage measurements by the null method. Observers in the past have measured probe voltages while zero current was being drawn to the probes. Effects such as insulating layers around the probes could give erroneous results by this method. (2) To compare the interface resistance of cathodes with pure nickel as base metal to that of cathodes with base metal consisting of nickel plus about 4 % silicon. It had been observed that cathodes with silicon in

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1. W. E. Danforth, "Cathode Coating Resistance as Measured by Embedded Probes," OSRD Division 14 Report 514, October 31, 1945.

2. Coomes, Buck, Eisenstein, Fineman, "Alkaline Earth Oxide Cathodes for Pulsed Tubes," Radiation Laboratory Report 933, March 30, 1946.

the base metal sparked at a considerably lower voltage than those made on pure nickel, and that a compound was formed on the nickel plus silicon base metal which Eisenstein had identified as barium metasilicate by x-ray methods. It was believed that cathodes made on Ni + Si base metal might have a higher interface resistance than those made on pure Ni. If this were true, sets of tubes with pure Ni and Ni + Si cathode base metals would permit one to study the effects of interface resistance on cathode emission and sparking. (3) To study coating and interface resistance vs. cathode operating time in an attempt to correlate either or both of these quantities with cathode life and with previously observed decreases in emission during cathode life. The following results have been obtained: For a constant anode pulse current, measurements have been made of probe voltage for several different values of pulse current drawn to the probes. From a plot of probe voltage vs. probe current the probe voltage at which the probe current is zero can be determined. Within experimental errors such values have thus far been found to agree with values measured with zero current flowing to the probes. Figure 1 shows a typical current-voltage characteristic of one probe of one tube. Ordinates are probe voltages in volts and abscissas are peak probe pulse currents in milli-amperes obtained by applying a low voltage pulse to the probe of the same shape and at the same time as a high voltage pulse is applied to the anode. They are the currents required to hold the probe at a given potential; + representing electrons flowing from the coating to the probe and - representing electrons flowing from the probe into the coating. From this curve the probe voltage at zero current is 45 volts which agrees with the value of 44.5 as measured with zero current flowing to the probes.

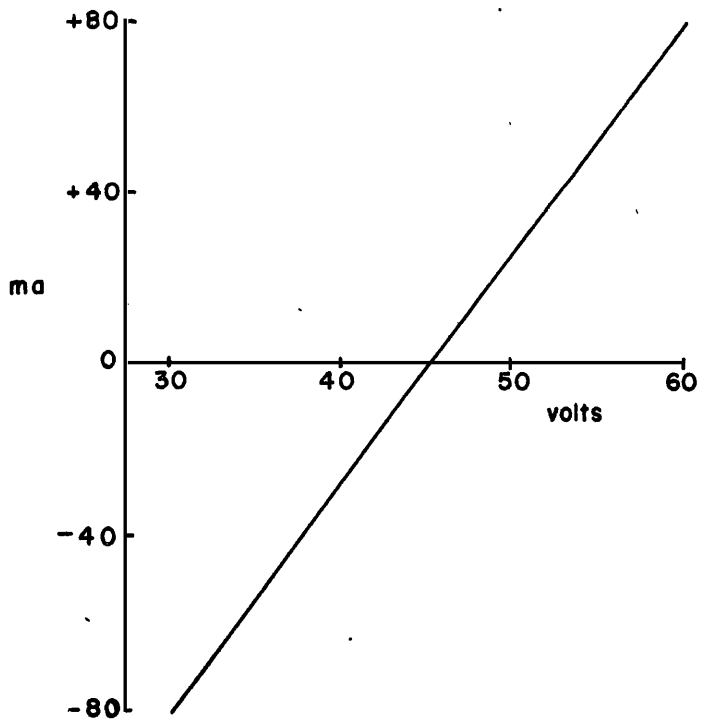


Figure 1.

Agreement under pulsed conditions between probe voltages as determined by the null method and from the current-voltage characteristic is in accord with observations made by Mutter under conditions of d-c operation where a similar agreement is found.

Fifteen tubes as described under part (2) have been made and studied. The cathode base consisted of a cylinder 3 mm. in diameter and 14 mm. long with 8 mm. coated, giving a coated area of 3/4 square cm. Nickel probe wires and an equal molar solid solution of BaO and SrO coating were used. Figure 2 shows typical interface resistance curves obtained on 3 different tubes with base metals of pure nickel. Figure 3 shows interface resistivity curves for 3 different tubes with base metals of Ni + 4 % Si. Figure 4 shows coating resistance vs. current for 2 tubes. Data for all 3 sets of these curves were obtained at 850° C. The curves of Figure 5 show interface resistance obtained on a given tube at 3 different temperatures.

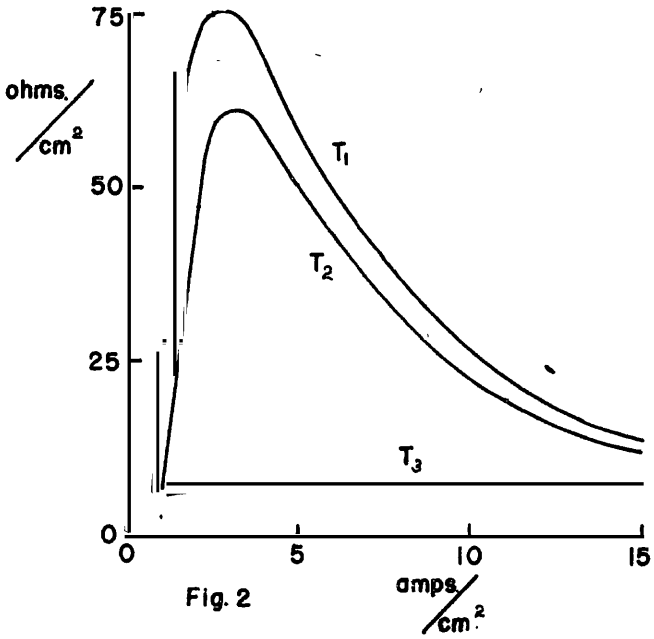


Fig. 2

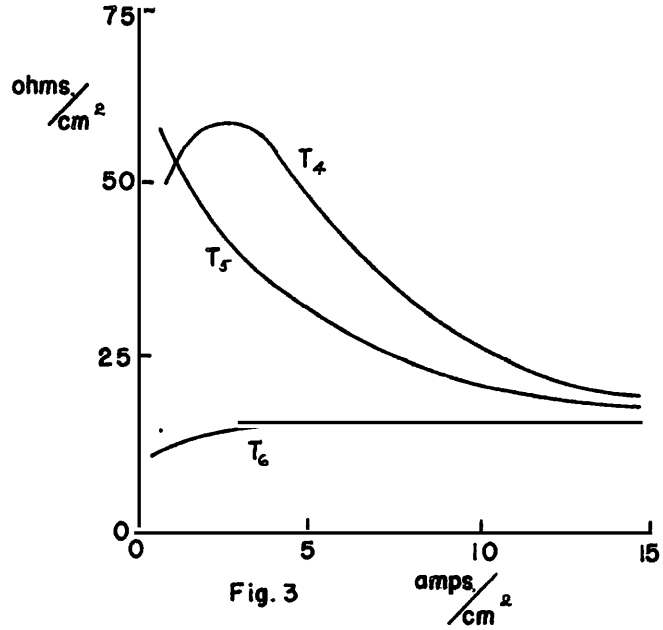


Fig. 3

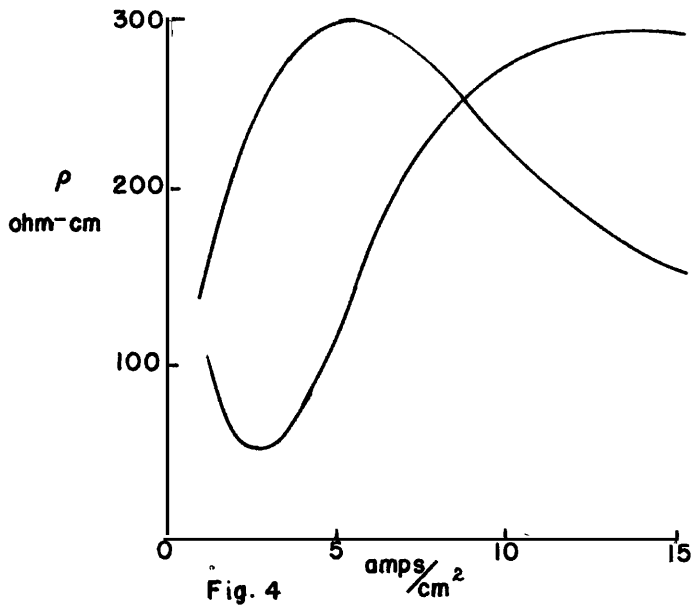


Fig. 4

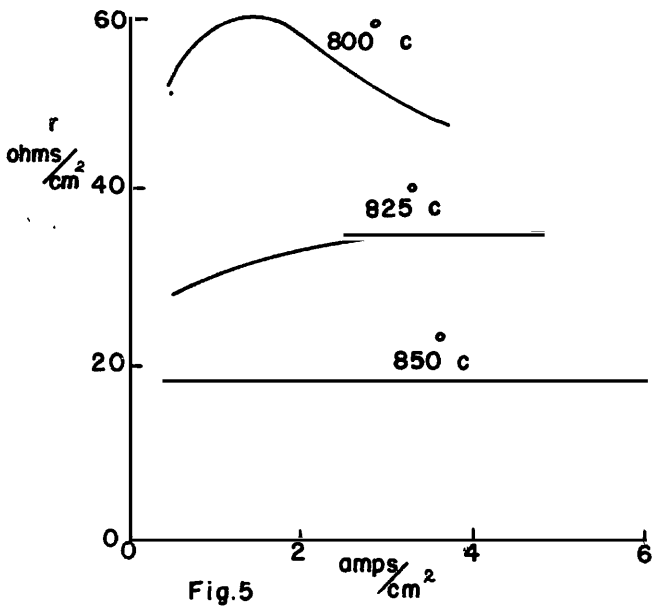


Fig.5

Curves T_1 and T_2 of Figure 2 are similar to those used by previous observers to justify the blocking layer model of an oxide cathode. However, in these 2 tubes in particular and others in general the coating was very poorly bonded to the base metal. Tapping the tube lightly would cause the coating to slide off. Thus, curves T_1 and T_2 of Figure 2 and other similar curves may be characteristic of base metal + vacuum layer or layer of poor bonding + oxide and not of base metal + blocking layer due to compounds formed at the interface + oxide. The coating of T_3 of Figure 2 was very much more tightly bound to the base metal than that of either T_1 or T_2. The fact that it does not show the blocking layer characteristic may indicate that if one has a tight oxide-to-base-metal bond the previously observed and reported anomalous interface resistance is not obtained.

One logical solution to this problem is to develop a probe technique which would enable one to obtain good oxide-to-base-metal bonding. The technique used previously is particularly bad in this respect, for the cathode is sprayed 3 times, and each coating must be thick enough to permit the probes to be wound on without shorting. It is also desirable to make the coating between the 2 probes as thick as possible so that the probe voltages will be appreciably different, thus increasing the accuracy of the coating resistance measurements. The result is a heavy coating which is no doubt more susceptible to cracking and pulling away from the base metal than a thin coating.

Another difficulty resulting from these heavy coatings is the fact that it is difficult to ascertain and control the temperature of the base metal and "interface layer" under the bulk of the coating by observing the temperature of the outside surface of the coating. In tubes of present design the difference in temperature between base metal and coating surface is of the order of 150° whereas it is about 60° in tubes with standard coatings. The temperature dependence of the interface resistance shown in Figure 5 makes this an important consideration.

At present attempts are being made to revise the technique so as to obtain reproducibly good bonding and consistent results. A flat cathode structure obtained from the Machlett Laboratories is being used. With this flat structure thinner coatings can be used without trouble with probe shorting than in the case where the probe wires have to be wound around a cylinder. Only one probe wire is being inserted which permits a still further reduction in coating thickness. It will not be possible to measure coating resistance in these tubes, but if the bonding is good and temperature difference low as expected, it should be possible to establish whether or not the sometimes observed anomalous interface resistance is real. Data to date show that when it is observed it is large compared to the coating resistance, so correction for the resistance of the coating between the base metal and probe in these tubes will not be necessary for present purposes.

Two tubes of this revised design have been made but the heaters burned out before the data were taken. If this approach fails the coating thickness will be further reduced by inserting no probe wires. The probe will be made in the form of a grid on a sliding mechanism which can be moved down after the cathode is processed until it just rests on the surface of the oxide coating.

Nothing final can be said concerning the comparative behavior of cathodes made on pure Ni and Ni + Si until a technique is developed which will give reproducible results on either one. However, the curves of Figures 2 and 3 indicate that there may not be much if any difference in regard to interface resistance.

In all these studies probe data have been taken at peak currents such that the emission was always space charge limited so as not to apply a field to the cathode and probe wires. It has been observed consistently that in calculating space charge conditions the cathode radius should be taken out at least to the surface of the coating. Indications are that it should be taken still farther out but present geometrical accuracy is not good enough to be definite about this. It should not be taken as the radius of the base metal cylinder alone except for thin coatings where the error may be negligible.

Some observations have been made of changes in interface resistance with operating time, but nothing definite can be said until tubes with uniformly good bonding can be made. Otherwise, one cannot tell whether he is observing effects due to changes in the interface or in the nature of the bond between the coating and base metal.

I. E. Electrometer Tube Development

Staff: Professor W. B. Nottingham

The two electrometer vacuum tubes that are now in most common use are the General Electric, FP54, and the Victoreen tube, VW-41. Both of these tubes suffer from a form of instability in steady operation that is related to the "anode effect." This effect has to do with the trapping of electrons on a metal surface that is not entirely free of surface films of oxygen for example.

The objective of a research that I have been carrying on has been the production of an electrometer tube that is not only free from the anode effect instability but also has more suitable electrical properties for use in actual operating circuits. Although the one tube that has been constructed did not possess the desired electrical characteristics, it served to establish a number of very interesting properties of electrometer tubes with particular reference to the currents that flow in the grid circuit.

The important components that make up the grid current are: 1) positive ion emission from the filament; 2) photo-electric emission from the control grid, due to the light from the filament; 3) electrons emitted

from the control grid due to the re-combination of dissociated nitrogen at the surface of the grid; 4) emission of electrons due to the light given off by excited atoms and molecules; 5) grid current due to the arrival of positive ions produced by electron bombardment in the gas; 6) electron emission from the grid due to the soft x-rays generated by the bombardment of the space charge grid and the plate of the tube during operations.

With a thoriated filament in a good state of activation the ion emission current density can be expressed by the following empirical equation:

$$i_+ = 750 \times 10^{-\frac{30,000}{T}} \qquad (1)$$

With the constants of the above equation, the current (i_+) is expressed in amperes per square centimeter. T is the temperature in degrees K . The range of temperature for which this equation applies extends from 1700° K to 2050° K. At the expected operating temperature of 1710° K, a positive ion emission of 4.3×10^{-17} amp. is to be expected from a filament of area 0.02 square centimeters. If the potential applied to the space charge grid is 4 volts or more then the ion current is reduced to a negligible value.

In the particular structure used, the electrons emitted from the control grid due to the light from the filament are constant and correspond to a current of 3×10^{-16} amps. at the operating temperature. Since this component of the grid current is practically independent of the grid voltage, it is not likely to influence the ultimate sensitivity that can be obtained from the electrometer tube. If the operating temperature is lowered to 1650° K, the photo-electric current produced by the light from the filament will be less than 10^{-16} amps. The equation by which the photo-electric current can be computed is the following:

$$i_{ph} = 7.5 \times 10^{-(3 + \frac{20,000}{T})} \qquad (2)$$

Although equation (2) gives the photo-electric current per unit area of the filament as a function of the temperature, it is true that this equation will apply only to the particular tube structure that we have used. However, it still may serve a very useful purpose since it furnishes a means of estimating the photo-electric current that might be obtained in almost any other relatively simple tube structure.

The residual gas likely to be found in a well evacuated tube is thought to be largely nitrogen. The electrometer tube when first constructed had a leak sufficient to cause the pressure to rise to 6.6×10^{-3} millimeters in 20 days. In the presence of this pressure of gas, it was possible to discover that electrons are emitted from the control grid when the bombarding electron energy exceeds 8.5 electron volts. This electron emission from the grid may be accounted for by either the re-combination of dissociated nitrogen molecules at the surface of the grid or due to electron emission resulting from the light given off from excited nitrogen molecules. When the electron energy exceeds the onset value by approximately

2 volts (specifically when the electron energy is near 10.5 volts), 3 electrons are emitted from the grid per 10^7 bombarding electrons at a pressure of one millimeter. It follows from this factor that the grid current contribution at approximately 10 volts would be 5×10^{-18} amps. in a well-evacuated tube where the pressure is 2×10^{-8} millimeters.

The onset of ionization in the gas has been observed to take place at approximately 15 volts which is in agreement with the ionization potential for nitrogen. The increase in ion yield is greatest between 30 and 40 electron volts. From 40 to 100 volts, the increase is slow but continuous. These facts have a bearing on the next and final contribution to the grid current of an electrometer tube that comes from the generation of soft x-rays as the electrons are absorbed on the space charge grid and on a plate of the electrometer tube.

After all of the other components of electrometer tube grid current have been subtracted from the total grid current, that remaining is thought to be the result of the absorption of the light in the far ultra violet range that is emitted from the surfaces of tube parts that are bombarded by electrons. Experiment shows that the yield of these photo-electrons resulting from the soft x-rays, increases quite accurately as the fourth power of the electron energy between the range of zero and 18 volts. Between 18 and 26 volts, there is a tendency for the yield to rise less rapidly. At 26 volts, there seems to be a critical potential after which again the yield continues along a fourth power line. This fourth power curve is followed up to 45 volts and between 45 and 100, there is a gradual transition from the fourth power down to the first power. From 100 volts to 700 volts, the yield of photo-electrons is almost directly proportional to the voltage. Between 500 and 700 volts, there seems to be a gradual increase in yield above that given by the linear relation. The power law applicable to these results would have an exponent of 1.1 to 1.2. Particular mention of this phenomenon of electron emission resulting from the absorption of soft x-rays is important because ionization gauges designed in the conventional manner are certainly limited in their suitable pressure range because of the background current that results from the absorption of these soft x-rays. At 200 volts, the observed ratio of i_x/i_e is 2.6×10^{-7}. The symbol i_x represents the soft x-ray emission current from the grid and i_e represents the bombarding electron current. The approximate pressure at which the gas current would be expected to be approximately equal to the x-ray current is 4×10^{-8} millimeters pressure. It follows therefore that if the apparent pressure as indicated by a conventional ionization gauge is 2×10^{-8} millimeters, then the true pressure may be nearer 10^{-9} than it is according to the ionization gauge measurement.

The program for the immediate future involves the construction of an ionization gauge so designed that it will be free from the serious x-ray current. Measurements will be made to determine whether or not this

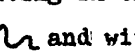
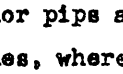
expected difficulty with conventional ionization gauges can be verified experimentally. The second step in the development of the electrometer tube involves the construction of a new tube with alterations in the grid structure that are expected to improve the electrical characteristics of the tube in terms of its intended purpose.

I. F. The Transmission of the Photo-effect in Silicon

Staff: Dr. F. C. Brown

It has been demonstrated that if one end of a 4.5 cm. silicon crystal is illuminated, there is an accompanying increase of electrical conductivity at the opposite end. This change is the same whether the current flows transversely or longitudinally. The immediate objective of the research is the measurement of the attenuation and the velocity of the effect, and the correlation of these results and later the major objective is the correlation of the results with the other electrical and optical properties in order to obtain a basic understanding of the phenomenon.

The velocity is measured by illuminating the crystal successively at two points through two windows in a disk rotating 30 or 60 times a second. The time at which the effect reaches the electrically conducting part of the crystal is measured on an oscilloscope.

With the disk rotating in one direction, the form of oscilloscope curve is thus  and with the rotation reversed the curve is  . The minor pips arise from the effect transmitted at a distance from the electrodes, whereas the major pips arise from illumination at electrodes. The time between the major pips and between the major and minor pips, makes it possible to compute the distance travelled by the effect, the time required, and the velocity. For the distance of transmission of 7 mm., the velocity has been determined to be 400 meters/sec. It is yet to be determined if this velocity varies with distance of travel and with temperature.

The attenuation was obtained by measuring the equilibrium conductivity when the crystal was illuminated at different distances from the electrode. If N is the number of electrons activated by the light, then the change of conductivity is a constant x N. The curve in the accompanying figure shows the variation of the effect with the distance of the illumination from the electrode. On the theory that the light effect frees electrons which are recaptured at rate α and which travel with velocity v,

$$\frac{dN}{dt} = -\alpha N^2 - v e^{-x}\left(\frac{dN}{dt}_{,}\right)$$

we get

$$\frac{1}{N} = \frac{\alpha}{v}(e^{x}-1) - \frac{1}{N_o}$$

The straight line is the plot of $\frac{1}{N}$ against $(e^{-x}-1)$. Thus for the direct

measurements of velocity, there seems to be no significant variation with distance of transmission, and there is a decided discrepancy between this and the attenuation experiments. This discrepancy may be due to variation of recapture coefficient with distance.

The Edgerton flash system has also been used using a light of estimated 3 microsecond duration. With this the velocity is of the same order as obtained with the rotating disk.