I MICROWAVE AND PHYSICAL ELECTRONICS

A CONSTRUCTION OF 5-MM OXFORD TYPE TUBE

Staff N G Parke

Description of Project In connection with the investigation of electromagnetic phenomena in the frequency region above 30,000 Mc, attempts are being made to construct a 60,000-Mc reflex velocity-modulated tube, the cavity for which is a scaled-down version of that used in the (24,000 Mc) 2K33 reflex klystron The mechanical features of the tube differ considerably from the parent tube The most important electrical change is the removal of the cylinder of glass situated in the outer cavity of the 2K33 This piece of glass now appears as a window in the output grid where it may interfere with the circuit efficiency but will not affect the conditions of oscillation

Status All the parts for a dozen tubes have been manufactured Fabrication problems contrive to consume a major part of the effort The outstanding problems appear to be (1) Brazing the Kovar Cup which carries the output window without cracking the glass tube which holds the electron gun (2) High-frequency induction heating of the gun without cracking the Kovar-Glass seal on this same tube (3) Securing sufficiently accurate gun alignment to pass a substantial portion of the beam through the 0 014" diameter gap All these problems arise essentially from the very small physical dimensions of these tubes

B HIGH-POWER MAGNETRON RESEARCH

Staff Professor S T Martin
J H Henry
R R Moats

Description of Project The objective of the high-power magnetron research project is to explore the fundamental engineering problems incident to the production and utilization of higher powers in the 3000 Mc/sec region of the frequency spectrum To provide a specific focus for this program, the design, construction, and test of a magnetron to operate at 10 Mw and 10 7 cm, with a pulse length of 5 μsec has been undertaken As an initial step, construction and test of a scaled-up version of the Columbia AX-9, a 3-cm rising-sun magnetron which has delivered 1 Mw at a pulse length of 1 μsec has been started The average input power has been arbitrarily chosen to be about 10 kw because of the limitations of the modulator

Status The problems of fabrication of this tube, which were mentioned in the last Quarterly Progress Report, now appear to be solved, at least in principle These problems were primarily caused by the large size of tube parts and the limited power-handling capabilities of the equipment used in various brazing operations The present status of work on this tube is (a) Cold tests of the anode are in progress (b) Preliminary tests to determine activation procedures for the large cathode required are being undertaken (c) Two additional tubes are being constructed by means of the stacked lamination technique

Two major problems clearly discernible in the achievement of the power output required, are the construction of a low-loss output window and the provision of cathodes more rugged than the oxide cathode Although it appears that the efforts of at least one group (in another laboratory) to work out the technique of assembly of low-loss ceramic windows are meeting with success, the comparative ease with which mica windows may be fabricated by the technique invented by J S Donal make this a distinctly attractive possibility, at least for experimental work Some effort is therefore being spent on investigating the suitability of mica windows of the large size ($3\frac{1}{2}$" diameter) required for the above tube To date progress on this work has been retarded because the chrome-iron alloy required for matching the thermal expansion of mica has not been obtainable in the sizes required, but these are expected in the very near future

The most promising candidate for a suitable cathode is the sintered thoria cathode, in spite of the numerous disappointments reported because of its poor mechanical properties Considerable effort has been committed to research on proper techniques for making these cathodes Progress to date on this problem has been confined to the manufacture and partial installation of an argon atmosphere furnace (with its controllable power source) which will attain the temperature (ca 2300°C) required for sintering the thoria

A side issue of some interest, which is being given some attention, is the comparison of actual and theoretically determined anode frequencies This question has arisen during the course of work aimed at changing the shape of the small cavities in the AX-9 without altering its π mode frequency or the separation of critically important modes Accordingly, it has been decided to compare the computed and experimentally determined anode properties of a series of rising-sun anodes (all having parallel-sided small slots), over a range of systematically varied parameters This comparison should yield insight into the nature of corrections required for more precise anode design In connection with this work five precisely constructed anodes are nearing completion

C CATHODE RESEARCH

1 Oxide Cathode Research

Staff Professor W B Nottingham
Dr A S Eisenstein
C S Hung
G W. Mahlman
W E Mutter

It is the purpose of this report to present a brief survey of the state of affairs regarding the agreement between oxide cathode theory and experiment as it existed in 1940, and to describe certain researches carried out at the Radiation Laboratory during the war years as well as current investigations at this laboratory

Although the oxide-coated cathode was discovered some 45 years ago, our present day understanding of the emission mechanism is far from complete The oxide cathode, as a copious source of free electrons, is figuratively the heart of most electronic devices Problems arising in its improvement and development are of considerable interest in the fields of both fundamental and applied electronic research In the past, considerable gains were made through a type of research in which many coating-base metal combinations were investigated An optimum combination which resulted was an approximate equal molar solid solution of barium strontium oxides (BaSr)O on a nickel base metal With this combination, these investigations were continued to include such parameters as particle size, density of packing, effect of impurities, etc Within more recent years, emphasis has been placed on first obtaining an understanding of the fundamental mechanisms of the oxide cathode from which it is expected better cathodes will result

The thermionic emission capabilities of cathode materials are generally represented in a plot of the logarithm of the maximum obtainable space-charge limited emission in amp/cm^2 versus the reciprocal of the absolute temperature of the cathode. A plot of this type is shown in Fig 1, taken from a review article by Blewett in 1939[1] and representing the d-c emission capabilities The superiority of the (BaSr)O cathode is readily apparent It is seen, however, that the high temperature emission of thoria (ThO_2)[2] is approximately of equal magnitude Wartime research in connection with pulsed magnetron cathode development showed that for emission pulses of microsecond duration the current densities obtainable from tungsten and thoria are in agreement with d-c measurements For (BaSr)O the peak emission at 850°C may in some cases exceed 100 amp/cm^2, a value two orders of magnitude in excess of that indicated in Fig. 1. At 900°C,

1 J Blewett, J App Phys 10, 668, 831 (1939).

2 Now called "sinthor" in the sintered state as developed at the Bartol Research Foundation

however, d-c emissions of 14 amp/cm^2 have been observed from similar cathodes Some question remains as to whether true space-charge limited conditions exist at the cathode during either of these measurements Emission data plotted in the form shown in Fig 1 may be represented by the empirical equation,

$$i = a \exp(-b/T) \qquad (1)$$

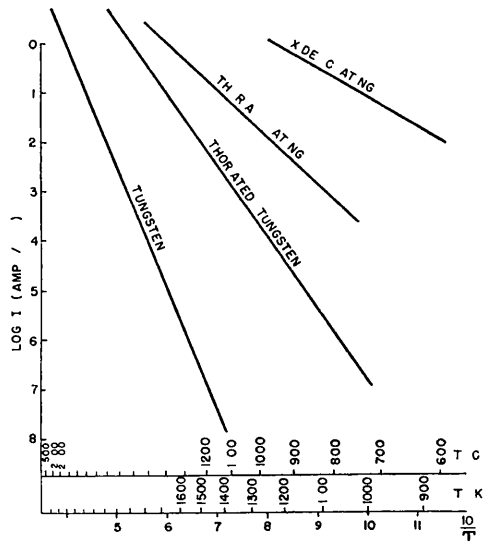

Figure 1 Emission data of several types of cathodes

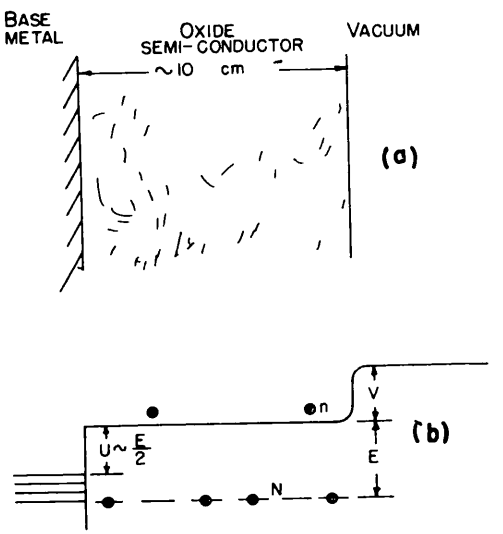

Figure 2 (a) Schematic representation of oxide cathode in cross section (b) Energy level configuration.

If we choose the form of the Richardson equation, then $a = AT^2$, and $b = e\varphi/k$ For oxide cathodes the value of the constant A depends on the state of activity T is the absolute temperature, φ the work function, e the electronic change and k Boltzmann's constant In practice, φ is determined from the slope of the curve.

Considerable success has been achieved in recent years in treating the oxide cathode coating as an excess semi-conductor by using the concepts of modern solid-state theory as first proposed by Wilson and Fowler about 1931 Figure 2(a) shows a schematic representation of the oxide cathode in cross section and Figure 2(b) shows the corresponding energy level configuration. In the base metal the filled band is indicated The uppermost energy level is called the Fermi level, and indicates the highest occupied electronic energy state at absolute zero Figure 2(b) shows an impurity level consisting of N impurity centers per cc at an energy E below the bottom of the conduction band At a temperature T, if one neglects electron transitions from the filled band of the semi-conductor, n electrons per cc are excited to the conduction band from the impurity level The lowest conduction level is separated from the Fermi level by an energy gap U and from the energy of an electron in the vacuum by an energy V By setting up the thermodynamic conditions of free energy within the semi conductor, it is shown that

$$n \propto N^{\frac{1}{2}} \exp(-eE/2kT), \qquad (2)$$

and the position of the Fermi level relative to the conduction band is

$$U = E/2 - kT \log\left(\frac{N^{\frac{1}{2}}}{4\pi mkT/h^2}\right)^{3/2}$$

where m is the electronic mass and h is Planck's constant In general the second term is negligible and U~E/2 Thus in this model the electronic properties of the cathode may be described in terms of three parameters (1) E, the activation energy, (2) V, the surface work function and (3) N, the density of impurity centers The Japanese group headed by Nishibori has attempted to test the self consistency of this cathode model by making measurements of the thermionic work function φ_{th}, the photoelectric work function φ_{pe}, and the conductivity activation energy E/2 On the basis of this model

$$\varphi_{th} = (U + V) \cong (E/2 + V) \qquad (4)$$

$$\varphi_{pe} = E + V \qquad (5)$$

Since the electrical conductivity σ is directly proportional to the density of electrons n in the conduction band, it is seen from (2) that a plot of the logarithm of σ versus the reciprocal of the absolute temperature gives a curve whose slope is eE/2k These workers have measured the conductivity of oxide-coated cathodes by making use of the voltage developed by a probe wire imbedded in the coating when an emission current is drawn from the cathode Since φ_{th} as obtained from (1), was measured with the same cathodes, a determination of both E and V were possible Values of φ_{pe} were obtained in a separate experiment and yielded results consistent with these other measurements (see Table I)

	Conductivity	φ_{th}		φ_{pe}
	E/2	V+E/2	V	V+E
BaO	—	—	—	1 63
(BaSr)O	0 65	0 95	3	1 66
SrO	1 1	1 4	3	2 58

Table I Values of E/2, V+E/2, and V+E obtained from measurements of conductivity, thermionic work function, and photoelectric work function, respectively, and the computed V

Thus is appeared in 1940 that within the rather wide experimental limits of the measurements, the modern impurity semi-conductor model adequately explained the observed behavior Wartime research introduced two experimental techniques which prior to that time had not been fully utilized in studying oxide-coated cathodes They were (1) pulsed measurements of thermionic emission and conductivity and (2) x-ray diffraction studies of the chemical and physical nature of the completed cathode structure

Accompanying the introduction of pulsed techniques for measuring conductivities at high current densities was the development of the double-probe technique which allows the determination of potentials which exist at two different levels within the coating Figure 3 shows in cross section, the general construction of the double-probe cathode Positive, microsecond voltage pulses are applied to the anode of the tube and the voltages assumed by the probes, with respect to the cathode base metal, are viewed on a synchroscope A measurement of the difference in the voltage developed by the two probes together with a knowledge of the current density being drawn through the coating

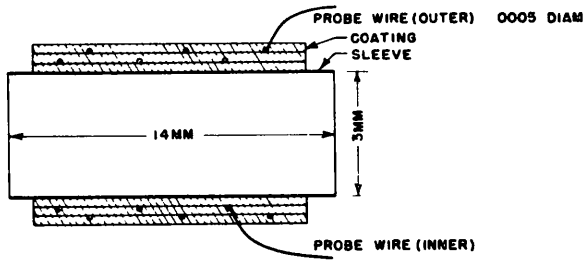

Figure 3. Construction of double-probe cathode.

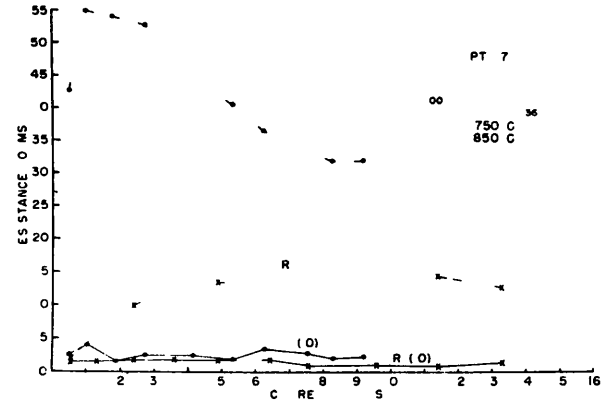

Figure 4. Cathode resistance characteristics.

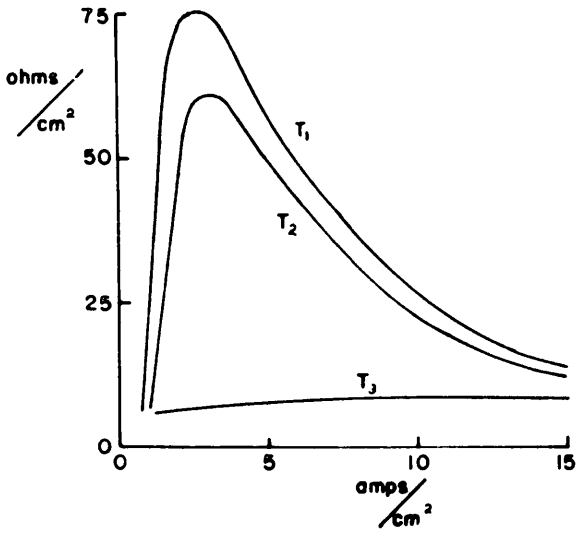

Figure 5 Interface resistance characteristics.

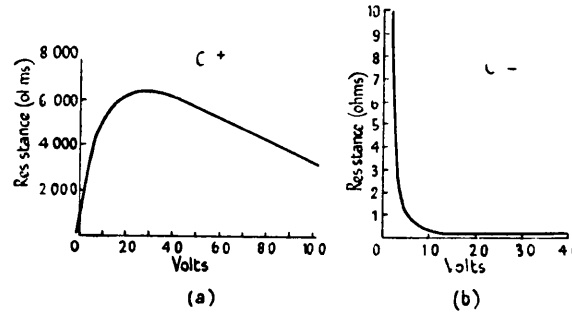

Figure 6 Blocking layer rectifier characteristics

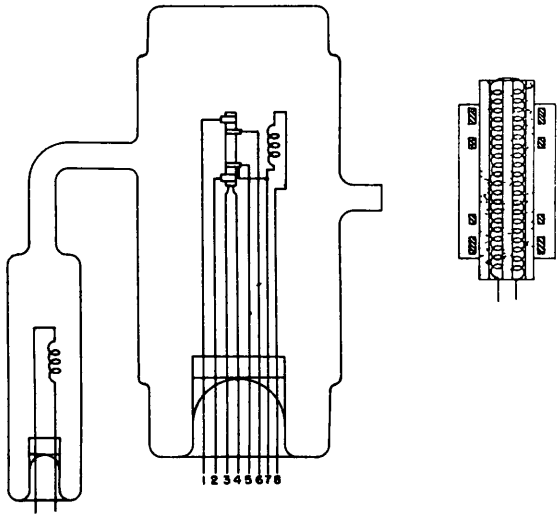

Figure 7. Conductivity tube construction.

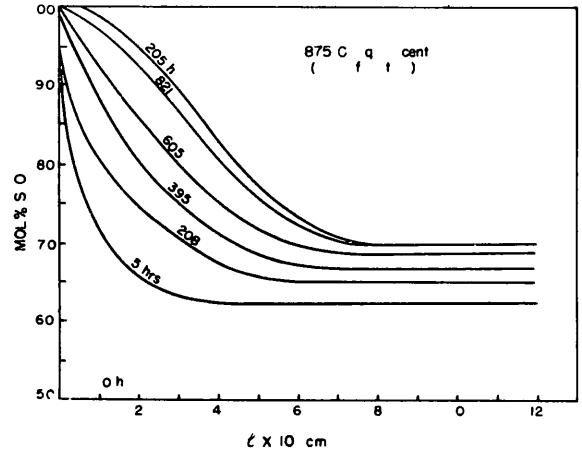

Figure 8 Variation of oxide composition with depth and time.

allows a calculation of the specific resistance of the coating between the probes. If one assigns this specific resistance to the coating layer between the base metal and first probe, one finds an excess voltage at this probe which may under certain conditions amount to several hundreds of volts This voltage is believed to exist at the interface between the base metal and coating If one arbitrarily divides this voltage by the current density, a quantity which is termed the interface resistance is obtained

A comparison of the interface resistance R_i and coating resistance R_c as observed in a double-probe cathode is shown in Fig 4 At temperatures of 750°C to 850°C and at high current densities, the interface resistance exceeds the coating resistance by a factor of 10 to 15. At low current densities, however, the interface resistance decreases and is frequently not detectable with d-c measuring techniques at current densities less than 1 amp/cm^2 as were used by the Japanese group Mutter has recently shown that at low temperatures the interface resistance can be measured with d-c techniques

Figure 5 shows the interface resistance observed by Dillinger in three cathodes, all made on a pure nickel base This wide variation in the resistance characteristics lead to the suggestion that curves T_1 and T_2 resulted from a mechanically poor coating-interface bonding and that T_3 represented the normal interface characteristic Additional evidence was obtained by Mutter, who found the T_3 type interface resistance in four tubes made on the pure nickel base Cathodes prepared on a base of 5 per cent silicon nickel, or chromium-plated nickel have shown an interface resistance which is non-ohmic and frequently of the type T_1, T_2

Within the past year a considerable amount of speculation has arisen regarding the origin of this excess voltage at the interface The least complex of these hypotheses considers an interface compound formed from a solid state chemical reaction between the base metal and coating, eg, $BaNiO_n$, $BaSiO_n$, $BaCrO_n$, which has a specific resistance considerably higher than that of the oxide coating This explanation can be considered as satisfactory only if the interface resistance is non-ohmic in such a manner as to give rise to a characteristic of the type shown in Fig 5, T_1, T_2

The striking resemblance between the interface resistance characteristics and those of the blocking-layer rectifier have lead to the suggestion that the physical nature of the two are similar Figure 6 shows the resistance-voltage characteristic of the copper-oxide rectifier as a well known example of the blocking-layer rectifier Mott and Schottky have independently explained the action of the blocking-layer rectifier in terms of the thermionic emission of electrons between a base metal and semi-conductor separated by a thin dielectric barrier layer If this model is extended to the oxide cathode a high resistance characteristic is expected (Fig 6(a)) for the flow of electrons from the metal to semi-conductor, and for the flow of electrons in the opposite direction a low resistance should result (Fig 6(b)).

Three suggestions have been made as to the nature of the sandwiched dielectric layer which is required by the blocking-layer hypothesis. These are (1) a vacuum layer, due to a poor metal - semi-conductor bonding as mentioned previously in the case of a pure nickel base, (2) an unactivated semi-conductor layer adjacent to the

metal, as in the case of the copper-oxide rectifier, and (3) an interface compound whose electrical properties are those of a dielectric The detection of blocking layers of types (1) and (2) would be most difficult, x-ray diffraction techniques, however, are quite suitable for detecting a layer of type (3)

When the oxide coating is removed from cathodes prepared on base materials containing Si, Cr, Ti, Mo, or Al, an interface compound is visible whose color depends on the particular base metal and coating used X-ray diffraction patterns obtained from these interfaces show a different interface compound to be present in each case Only for the combinations BaO or (BaSr)O on Si-Ni has the interface material been identified In this case it is Ba_2SiO_4

The finding of an excess voltage at the cathode interface as well as unsuspected interface compounds does not necessarily imply that the voltage is due to the compound itself for reasons previously set forth In the case of the silicon interface, the interface material Ba_2SiO_4 has been prepared synthetically and its bulk electrical conductivity compared with that of the ordinary oxide coating (BaSr)O Figure 7 shows the conductivity tube used in this comparison The cross-sectional drawing on the right indicates a ceramic tube which is heated internally by means of a tungsten coil The oxide or silicate is applied to the external surface of the ceramic This coating contains four imbedded nickel probes, which are used in measuring the specific electrical conductivity as a function of temperature Preliminary measurements indicate that the silicate is an impurity semi-conductor with a specific conductivity from 10 to 1000 times less than that of the oxide in the temperature range $1100^{\circ}K$ to $1300^{\circ}K$ The activation energy E/2 of the silicate is greater than that of the oxide by a factor of about two This may explain the appearance of an interface resistance in the d-c measurements at low temperatures only At present, it seems difficult to account for the observed non-ohmic nature of the interface resistance on the basis of a straightforward electronic conductivity alone

An x-ray comparison method has been used to determine the thickness of the interface layer found in actual Si-Ni cathodes Layers were observed which had an average thickness in the range 5×10^{-4} to 10^{-3} cm or 1/20 to 1/10 of the total coating thickness (see Fig 2(a)) Since the specific conductivities of the interface and coating differ by a factor of as much as 100, it is seen that on the basis of resistance alone the voltage developed at the interface may exceed that developed in the coating by a factor of 10 or greater

Current experiments being conducted by Hung are designed to determine the distribution of energies with which electrons emerge from the external oxide surface Should this energy distribution change as the base metal and interface type are altered, it is possible that the nature of the interface barrier will be revealed

Measurements of the thermionic work function and voltage- and current-sparking characteristics have been studied by Mahlman with multilayer cathodes in an attempt to evaluate the relative effects of certain types of coating at the interface and at the external surface Since the activation energies of the different coatings vary considerably (Table I), it is expected that variations of composition within the

oxide coating would modify the energy level configuration pictured in Figure 2(b)

For many years it has been known that a cathode which was initially equal molar in composition, (BaSr)O, would rapidly lose BaO from the surface when heated, because of the preferential evaporation of this component An x-ray analysis method has been developed which permits a determination of the variation of oxide composition with depth below the surface Figure 8 shows the result of one such analysis on a cathode which was examined at intervals during a period of 1200 hours in which it was heated at a temperature of 875°C Both bulk changes of composition as well as surface changes are to be observed In general these surface inhomogeneities are to be found within a layer of some 10^{-3} cm thick or 1/10 the total coating thickness Correlations between the electrical properties of the cathode and these surface changes are as yet problematical It seems reasonable, however, that alterations in the energy level configuration (Fig 2(b)) are inevitable The effects of certain base metal impurities and high d-c current drain are now being investigated to determine their influence on the rate of change in coating composition

Thus it is seen that the present day concept of the oxide cathode is very complex indeed and it does not seem strange that 45 years of research and development have not as yet lead to a complete solution of the oxide-coated cathode problem

The various phases of the problem in which progress is currently reported are coating studies, interface studies,and electron emission in accelerating and retarding fields

1 a. Cathode Interface Studies

Dr A S Eisenstein

The interface formed on oxide cathodes prepared on a Si-Ni base material is particularly suitable for study as it can be synthesized in bulk This synthesis involves a solid state, chemical reaction between equal molar proportions of $BaCO_3$ and SiO_2 which gives a compound whose composition was reported[1,2] as barium metasilicate, $BaSiO_3$ More recent work has shown its true identity to be barium orthosilicate, Ba_2SiO_4 In the temperature range 800°C to 1100°C, only the orthosilicate is formed even though the $BaCO_3$,SiO_2 constituents are mixed in the proportions 1 1 or 2 1, respectively At 1500°C in H_2, the composition ratio determines the compound which is formed X-ray diffraction analyses were used to detect these changes in composition

Having synthesized the interface compound, the specific electrical conductivity was determined and compared with the conductivity of the oxide coating (BaSr)O As yet, some uncertainty exists as to the true temperature range over which measurements were obtained, in general, however, the silicate conductivity is less than that of the oxide by a factor of 10 to 100 X-ray measurements have shown the silicate interface of

1 W Jander, Z anorg allgem Chem , 163, 8 (1927)

2 A F Fineman and A Eisenstein, J App Phys , 17, 663 (1946)

actual cathodes to be roughly 1/10 of the total coating thickness Thus it appears reasonable that when emission current is drawn, the voltage drop which appears across the interface may exceed that across the coating These measurements are being extended to (1) determine what changes in the interface thickness occur with increasing cathode life, (2) measure coating and interface conductivities over wide ranges of activity, and (3) study the solid state reaction of $BaCO_3$, SiO_2 in vacuum

1 b The Interface as a Blocking Layer

W E Mutter

It has been suggested that the appearance of interface potentials in oxide cathodes may be explained on the basis of the theory developed by Mott[1] to describe blocking-layer oxide rectifier operation If this analogy is reasonable, one might expect that the interface potentials developed when high current densities are passed in the reverse direction (i e , electrons flowing from vacuum to coating to base metal) will be considerably lower in magnitude than those observed in the forward direction

As a logical extension of our present probe work, some experiments have been made to measure interface potentials appearing with reverse current Two tubes of cylindrical symmetry have been made These consist of a central primary oxide cathode with a pure nickel base and two probes, a cylindrical shield exposing only the central coated length of the cathode, and a secondary internally coated cylindrical cathode occupying the normal anode site The probe potentials on these tubes have been measured as a function of the pulsed cathode current density in both directions Preliminary results on the two tubes indicate that the magnitude of the interface potential for a given current density up to 5 amp/cm^2 and at 800°C is approximately the same whether the cathode current flows in the normal or reverse direction This is not what one would expect from the blocking-layer theory This initial result must be considered with reservation, however because (1) the conditions of temperature and current density must be broadened and (2) some aspects of the experiment require further study to insure the validity of the initial result These are the effect of bombarding the primary cathode with high-energy electrons from the secondary cathode, heating effects some uncertainty in the effective area of the primary cathode, and effects of secondary electron emission from the primary cathode

A third tube embodying the same principle as described above has been built This tube has two flat circular oxide cathodes (each with probes) which face each other at a very small distance of separation It has experimental advantages over the other design and will be used to check results on the first two tubes

1 c. Coating Studies

G M Mahlman

It was reported in the last Quarterly Progress Report that 16 tubes consisting of layers of BaO,SrO were undergoing tests of their sparking properties Tests in early stages of life yield two results (1) Pure BaO coatings fail to spark with the

1 N F Mott, Proc Roy Soc A171, 127 (1939)

peak voltage available (approximately 16 kv or at a field of 90 kv/cm) whereas SrO and layers of BaO and SrO spark readily at voltages varying from about 5 to 15 kv Variations of sparking potential with temperature seem too erratic to make any general statement concerning them (2) The results of rather crude Richardson plots indicate the constants A and φ of Richardson's equation are related as follows over a range in φ from 1 volt to 3 5 volts

$$\log_{10} A = -6\ 8 + 4\ 64\varphi$$

2 Spectral Emissivity of Tungsten

Staff Professor W B Nottingham
W E Mutter

The project for the measurement of the spectral emissivity of tungsten has been temporarily interrupted because of the delayed installation of the generator required to operate the tube The project is still active and a report of results will be made available as soon as possible

3 Electron Emission in Accelerating and Retarding Fields

Staff Professor W B Nottingham
C S Hung

Description of Project An experimental tube has been constructed with a cathode approximately six inches long surrounded by collecting electrodes that are co-axial with respect to the cathode, and divided so that electron emission from the central portion of the cathode can be measured without disturbances caused by non-uniformities at the ends of the cathode The cathode was prepared by applying the standard fifty-fifty barium-strontium carbonate to a nickel base metal The collecting electrodes were constructed from tantalum and were extensively heat-treated prior to the insertion of the cathode In order to minimize the condensation of material on the anode, the cathode was "broken down" and activated by heat received from the anode which was heated by induction currents Thus the collecting electrodes were maintained as hot as possible during the cathode activation period The normal cathode heater was out-gassed by quick flashing at relatively high temperatures In spite of the precautions taken, it was impossible to keep the anode sufficiently clean in order not to cause measurable deactivation of the cathode when the anode was severely bombarded

A two-mil tungsten wire was welded to the inside surface of the nickel sleeve constituting the cathode base metal The nickel-to-tungsten junction thus formed served as a thermocouple for measuring the temperature of the cathode Temperature changes as small as 0 1°C were detected by this means As a result of calibrations made, the temperature of the cathode could be determined within a very few degrees It is necessary to use a technique of this kind since the temperature range, over which studies are planned, extends from approximately 350°K upward

Status This first experimental tube suffers from three disadvantages (1) unsatisfactory uniformity of the cathode, (2) objectionable material condensed on the inner surfaces of the anodes, (3) electrical leakage over support insulators In spite of these objections some rather interesting tentative results have been obtained

For the range of temperatures from 485°K to 650°K, the electron emission current has been measured as a function of the retarding potential applied to the collecting electrodes The slopes of the curves, plotted as the logarithm of the current against the retarding potential, agree remarkably well with the theoretical slope, calculated on the basis of the thermocouple temperature measurement when the retarding potential is the greatest that can be used in this particular tube As the retarding potential is decreased, there seems to be marked deficiency of slow electrons This result may be interpreted as an indication that electron reflection exists as the electrons attempt to excape from the cathode Until further experiments are done, this result must be considered as only tentative

An investigation of the emission for accelerating fields has been made covering a temperature range of 396°K to 517°K The computed electric fields set up at the surface of the cathode extended from 0 up to 25,000 volts/cm When plots are made of the logarithm of the current as a function of $\sqrt{E}/T$, the curves are very largely the same, independent of the temperature, and for values of $\sqrt{E}/T = 0\ 15$, the observed slope is approximately six times greater than that computed from the Schottky theory Attention is called to the fact that the Schottky theory depends on the assumption that reflection effects may be neglected At the highest value of $\sqrt{E}/T$, the slope of the plotted curves has dropped to about half its initial value, to become three times the theoretical slope

Although an effort has been made to get as much out of the present experimental tube as is reasonably possible, other tubes will have to be made with improved design in order to eliminate some of the objectionable features associated with the one upon which the results thus reported depends There is no doubt that more uniform cathodes, cleaner anodes, and reduced insulator leakage can be obtained

D IONIZATION GAUGE RESEARCH

Staff Professor W B Nottingham
L Sprague

As a consequence of an investigation, partially completed, on the development of a new type of vacuum tube electrometer, studies have been made in recent months of vacuum techniques and special designs of ionization gauges for the measurement of high vacua The work is in progress but the results to date are not sufficiently well established to warrant publication at this time

E PROPERTIES OF CATHODE-RAY SCREENS

Staff Professor W B Nottingham

During the War, a small group in the Radiation Laboratory was responsible for the determination of some of the properties of cathode-ray tube screens that are still being produced A sub-committee of the R M A (Radio Manufacturers Association) identified by the letters J E T E C , has been functioning over the past year or more to try to coordinate the descriptive information by which cathode-ray tube screens may be identified Since the investigations made at the Radiation Laboratory served as a valuable source of quantitative information, it has been considered to be within the scope of this laboratory to cooperate in every way possible to assist the manufacturers

of cathode-ray tubes in the presentation of design data, and in the formulation and standardization of test procedures for the determination of cathode-ray tube screen properties It has been the intention of this laboratory to establish a research project by which the properties of new screen materials could be investigated under well standardized and controlled conditions The equipment for such studies is partially available, and it is anticipated that when time and manpower become available, a more active interest in researches of this nature will be developed It is impossible to state at present, how long it will be before this research project will be well under way

F TRAVELLING-WAVE AMPLIFIER TUBES

1 Theoretical Considerations

Staff Dr L J Chu
J D Jackson

The broad classification of travelling-wave amplifier tubes includes all those devices in which the electrons, through interaction with a travelling wave lose energy, and produce an amplified electromagnetic wave

The electrons must travel with a velocity approximating the phase velocity of the travelling wave in order that an appreciable energy interchange occur Thus it is apparent that the guide for the wave must be so constructed that the phase velocity of the wave is considerably less than the velocity of light Then reasonably low energy electrons may be employed in the tube

There are several methods of obtaining a reduced phase velocity, one of which employs a spiral helix as the waveguide The wave can be thought of as travelling around the helix in a cork-screw manner with a phase velocity along the axis greatly reduced because of the small pitch of the windings

Early work on the helix tube as an amplifier was begun during 1944 at the Clarendon Laboratory Oxford by R Kompfner and E E Vickers[1] More recently Bell Telephone Laboratories has been doing extensive work in this field[2]

The theoretical discussion given here has been restricted to an analysis of the helix type of travelling wave amplifier tube with the electrons projected along the axis

Electromagnetic Field Solution outside the Space-charge Region Maxwell's equations can be solved in the helix by assuming the artificial boundary condition that current flow in the outer conductor is constrained to a direction making a constant angle with the axis of the helix The solutions for the field components allow the setting-up of an admittance function, H_φ/E_z , on the inner boundary, that of the cylindrical space-charge region The admittance is a function of the physical dimensions of the tube and

1 C V D Report C L Misc 26, 28

2 Preliminary reports by J R Pierce, BTL, (May, 1946)

the propagation constant of the wave, as yet undetermined The admittance is purely imaginary when the propagation constant is purely imaginary, and has a zero and infinity very close to each other The zero of this admittance function, if the radius of the space-charge region is allowed to go to zero corresponds to the case where no electrons are present Then he propagation constant is that of the ordinary, unperturbed wave in the helix The role played by the infinity of the admittance function will be apparent later

Electromagnetic Field Solution within the Axial Space-charge Region The electrons are assumed to occupy an axial cylinder of small radius The solution of Maxwell's equations within this cylindrical charge-filled region results in another admittance function, H_φ/E_z, at the outer boundary of the electron beam This admittance is a function of the propagation constant and the initial electron velocity The motion of the electrons in the field is assumed to be confined to the axial direction, that is, the radial components of the force are neglected The further assumption is made that the r-f components of the charge and current vary with the same propagation constant as the wave (These assumptions are the same as those made by J R Pierce) This analysis, then, takes account of the longitudinal space-charge effect in the electron beam

Combination of the Electronic and Field Solutions The continuity of H_φ/E_z at the outer boundary of the electron beam demands the equating of the two admittance functions The resulting equation is rather complicated in form, but can be approximated to a high degree of accuracy by a simple cubic equation with the propagation constant as variable, and the initial electron velocity as a parameter In order to obtain the cubic equation, it was necessary to make a first-order approximation in the space-charge solution This approximation, however, is at least better than neglecting the space-charge effect completely in calculating the fields acting on the electrons

The three roots of the cubic equation can be thought of as indicating three different wave components co-existing in the helix One root is purely imaginary over the whole range of electron velocities Except for a limited range of electron velocities, the other two roots are also purely imaginary This means that amplification will be obtained only over this range of electron velocities

The range for which amplification occurs extends from an upper limit somewhat above the unperturbed phase velocity to a lower limit, below the unperturbed phase velocity, that corresponds approximately to the infinity of the external admittance function

These results seem to differ from those obtained by J R Pierce in that there is a definite lower, as well as upper, limit of electron velocities for which amplification can occur

2 Experimental Studies

Prof J B Wiesner
L A Harris

Description of Project The theoretical investigation by L J Chu and J D Jackson indicates that a travelling-wave tube can be expected to operate in the 3-cm region as a broadband amplifier, and development of such a tube is being started

Status A magnetic focussing coil has been constructed and an electron gun is now being made in the Tube Laboratory Measurements are under way on a dummy helical line to determine the conditions necessary for matching to the input and output waveguides

G THE TRANSMISSION OF ENERGY FROM RADIATION ON SILICON CRYSTALS

Staff Dr F C Brown

The work on transmitted photoconductivity has been brought to a temporary conclusion and the results may be summarized as follows

Pulsed radiation, of duration 3 to 60 μsec incident on silicon crystals, produces an effect that is propagated along the crystal with a velocity of 400 meters/sec The effect is detected and measured through change of resistance of the crystal

Since the velocity is of the same order of magnitude as that of a thermal pulse, further experiments were conducted to check on whether the effect is thermal in nature A thermocouple attached to the crystal showed a transmitted temperature rise accounting largely for the resistance change There was inappreciable transmission if metal flats extending between the electrodes and the point of impingement of radiation, pressed against opposite crystal faces (Fig 1) Neither black paint nor opaque wax on the crystal materially altered the so-called photo effect, i e , the effect depends on the energy received

Finally, the pulsed energy was transmitted to the crystal electrode contact over a tungsten wire and repeated by transmission over a nickel wire The resistance changes of the crystal were almost identical with that incurred when the energy was transmitted ove the crystal itself The measured velocity in tungsten is 730 meter/sec and in nickel 250 meters/sec

Experimental evidence indicates that the photoconductivity in silicon crystals can be readily explained as a thermal effect, and it would be interesting to confirm this conclusion with a theoretical analysis verifying the experimental velocity of transmission, viz , 400 meters/sec

The Seat of the Resistance Experiments were made on the photo-sensitivity of the crystals when the initial resistance was varied by both temperature and pressure If a silicon crystal is under pressure applied at opposite electrodes or if the temperature of the crystal is made to change adequately, the resistance may be made to vary as much as a thousand fold

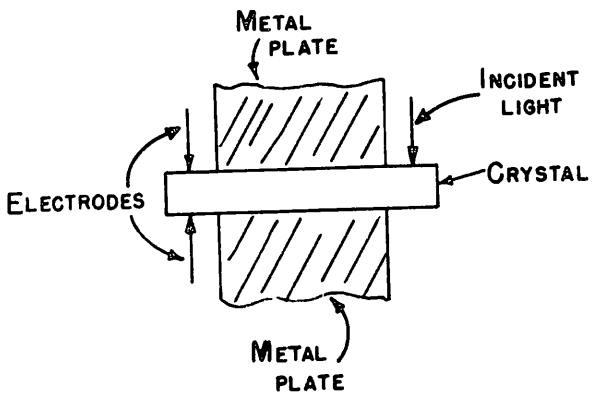

Figure 1

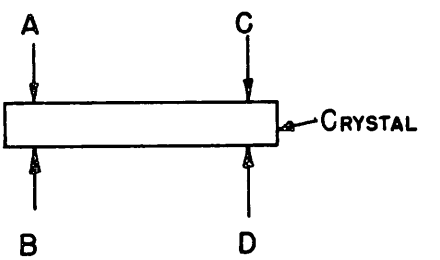

Figure 2

In order to determine the magnitude of the contact resistance compared to that of the body of the crystal the former was measured by a simple direct method A silicon crystal 0 8 mm in diameter and 1 cm long was mounted with tungsten electrodes at A, B, C and D degassed in high vacuum Distance C to D is 0 8 mm A to C 1 cm (Fig 2)

Suppose the resistance at each contact to be R_c Let ρ_1 be the specific resistance of the crystal at room temperature By measuring the total resistance across the crystal and also lengthwise it was easy to compute the contact resistance R_c and specific resistance ρ_1 at room temperature, and the same constants R_{c_2} and ρ_2 for the temperature 1120°C The ratio of contact resistances for the temperatures mentioned is $R_{c_1}/R_{c_2} = \frac{93.34}{385} = 242$ The ratio of the specific resistances is $\frac{\rho_1}{\rho_2} = \frac{.882}{0035} = 252$

It may be concluded that the rate of change of resistance of the body of the crystal and of the contact is the same and we therefore assume that both resistances may be treated as one The magnitude of the change of resistance is at least exceptional and it is gratifying that from here on we may consider the theory essentially from the basis of the crystal itself The implications of the usefulness of these crystals will be obvious

The Law of Change of Resistance with Temperature A very simple theory seems to explain adequately the magnitude of the resistance change In the main the electrons are held within the fields of the atoms and vibrating therein in thermal equilibrium The conductivity is proportional to the number of electrons that have sufficient energy to escape beyond the field of force of the atoms Thus the resistance and temperature are related as follows

$$\log R_1 - R_2 = \text{const} \quad (T_2 - T_1)$$

This relationship has been verified for some crystals between the temperature of boiling nitrogen and room temperature and for others between room temperatures and 1200°C It should be noted that conductivity densities have been found between 12 ma/cm^{2}volt and 4000 amp/cm^{2}volt.