PHYSICAL REVIEW VOLUME 85, NUMBER 2 JANUARY 15, 1952

Proceedings of the American Physical Society

MINUTES OF THE MEETING OF THE DIVISION OF ELECTRON PHYSICS AT THE NATIONAL BUREAU OF STANDARDS, WASHINGTON, D. C., NOVEMBER 1–3, 1951

Symposium on Electron Emission Phenomena in Commemoration of the Bureau's 50th Anniversary

A1. Address of Welcome. W. R. BRODE, Assistant Director, *National Bureau of Standards.*

A2. Atomistic Theory of the Metallic Surface. CONYERS HERRING, *Bell Telephone Laboratories.*

A3. Electrical Properties of Porous Semiconductors.* E. B. HENSLEY, *University of Missouri* (*now at Research Laboratory of Electronics, M.I.T.*).—Currently in the literature there are two theories concerning the conduction mechanism in oxide coated cathodes. One regards the crystals of the porous aggregate as simple *n*-type semiconductors with the conduction current passing electronically through the crystals. The other maintains that the conduction current at the higher operating temperatures is carried by the electron gas in the pores of the aggregate. An analysis of this second hypothesis will be discussed pointing out the conditions under which pore conduction will occur. The results of this analysis show that while the temperature dependence of the conductivity of an oxide cathode is compatible with the pore conduction theory, the ratio of the conductivity to the thermionic emission as reported in the literature is somewhat too large. An aggregate in which there are two parallel mechanisms for conduction will, in the presence of thermal gradients, possess two sources of thermoelectric emf. A simple theory for the thermoelectric power of the electron gas in the pores of a porous semiconductor is developed and the manner in which it combines with the normal thermoelectric power of the crystals will be analyzed. In most respects the results are in good agreement with the experimental data obtained by Young. However, the essential feature in this agreement appears to be the presence of two parallel mechanisms.

* Supported in part by the ONR.

A4. Electrical Conductivity and Thermoelectric Power of (BaSr)O and BaO.* J. R. YOUNG, *University of Missouri* (*now at General Electric Research Laboratory*).—A study has been made of the thermoelectric power, the electrical conductivity, and the thermionic emission of (BaSr)O and BaO at different states of activation and on different base metals over a temperature range of 1100°K to 300°K. A plot of the logarithm of the conductivity *vs* reciprocal temperature showed two straight line regions. The temperature dependence of the thermionic emission was found to be the same as the temperature dependence of the conductivity in the temperature range 700°K to 1100°K. The slope of a plot of the thermoelectric power *vs* reciprocal temperature was also similar to the thermionic work function and the conductivity activation energy in this temperature range. The thermoelectric power varied with temperature from a value of about 2.0 mv/° at 1100°K, increasing to about 2.5 mv/° at 800°K, reducing to between 1.0 and 0.5 mv/° at about 500°K, and remaining practically constant or increasing slowly at still lower temperatures. In all thermo electric power measurements the hot junction was positive indicating negative charge carriers. The simple semiconductor theory does not adequately account for these results which seem to be in good agreement with the pore conduction hypothesis.

* Supported in part by the ONR.

A5. Application of Nijboer's Theory to the Semiconducting Emitters and Its Modification. T. ARIZUMI AND S. NARITA, *Kobe Kogyo Corporation.*—Applying Nijboer's[1] theory to the semiconducting emitter the emission formulas applicable to any activated state have been easily deduced but recent studies on the Hall coefficient and electrical conductivity seem to suggest the coexistence of both *n*- and *p*-type conduction. Our measurements on the conductivity of the oxide coated cathode, in which pure MgO was used as the base, support this suggestion and moreover, recent experiments of Ishikawa and others[2] have revealed that the conductivity increased gradually and at the same time, the Hall coefficient changed its sign at higher oxygen pressures of about 10^{-1} to 100 mm Hg[5] Assuming that excess oxygen atoms are responsible for the formation of *p*-type level, some modification to the previous theory will be postulated. The obtained results are qualitatively in satisfactory agreement with the experiments on the conductivity and the thermionic work function.

[1] B. R. A. Nijboer, Proc. Phys. Soc. (London) **51**, 575 (1939).

[2] Y. Ishikawa and others, unpublished (oral presentation to Japan Electron Emission Committee).

B1. Chemical Reactions in Barium Oxide on Tungsten Emitters. R. C. HUGHES, P. P. COPPOLA, AND H. T. EVANS, *Philips Laboratories, Inc.*—When barium carbonate is heated in vacuum in contact with tungsten, the following reactions may occur in sequence as progressively higher temperatures are reached: (1) $WO_3+BaCO_3\rightleftarrows BaWO_4+CO_2$; (2) $3\,BaCO_3+W\rightleftarrows Ba_3WO_6+3CO$; (3) $BaCO_3\rightleftarrows BaO+CO_2$; (4) $6BaO+W\rightleftarrows Ba_3WO_6+3Ba$. At approximately 600°C, reaction (2) occurs with appreciable speed. Reaction (3) proceeds at 800–900°C. Reactions (2) and (3) may proceed simultaneously, preponderance of one over the other depending upon state of subdivision and intimacy of admixture of the reactants. Under favorable conditions reaction (2) may be driven to completion with almost total absence of reaction (3). Reaction (4) progresses with appreciable speed over approximately 1000°C.

Activated cathodes of BaO on W will normally have an interface of Ba_3WO_6 formed by reactions (2) or (4), or both. The end result of heating the cathode is the conversion of the entire thickness of the oxide coating to the basic tungstate. The resulting coating of Ba_3WO_6 on W is unreactive and nonvolatile at temperatures up to 1300°C, and provides no significant thermionic emission.

B2. The Production of Sr Metal in the Reduction of SrO by Methane. H. W. ALLISON AND GEORGE E. MOORE, *Bell Telephone Laboratories.*—The rate of this reaction is readily measurable at temperatures above about 1100°K by using radioactive isotopes. A pure platinum wire, serving as the mechanical support for radioactive SrO, can be heated to any temperature of interest but is itself chemically inert. The SrO can thus be maintained at a pyrometrically observed temperature in methane and the Sr metal, produced in the reaction, deposits on the bulb or on auxiliary filaments where it is measured by counting techniques. Present results indicate that the methane first dissociates into carbon and hydrogen, the carbon being primarily responsible for the reduction. SrO is reduced by methane at a rate considerably more rapid than by tungsten,* but less rapidly than the theoretical maximum rate, which can be predicted from thermodynamics.

Atomic hydrogen should leave no contaminant, such as carbon, in the oxide; and thermodynamic calculations indicate that it should be a more powerful reducing agent than methane. It will be examined experimentally.

* G. E. Moore and H. W. Allison, J. Chem. Phys. 18, 1579 (1950).

B3. The BaSrO Cathode Supported on an Insulator. George E. Moore and H. W. Allison, *Bell Telephone Laboratories.*—Preliminary results were presented in 1949.* Much physical and chemical complexity inherent in practical (BaSr)O cathodes could be eliminated and the interpretation of experimental data thus simplified if one could investigate the (BaSr)O layer without its usual metallic support. This was accomplished by supporting the layer on MgO ceramic, a chemically inert insulator. Measurement of electron emission from the insulated (BaSr)O required microsecond pulse technique. Pyrometer temperatures of the translucent cathodes were corrected by determining radioactively the evaporation rate of BaO and SrO, which are known functions of true temperature. Electron emission from these nonmetallically supported (BaSr)O layers is at least 5 orders of magnitude greater than from the uncoated MgO, a result consistent with generally accepted semiconductor theory which assigns no fundamental importance to the metal support. However the emission is 2 to 3 orders of magnitude less than from practical cathodes and is not increased significantly by treatment in atomic hydrogen or methane. Evidence given in the preceding paper indicates that BaO should be reduced by such treatments, whose ineffectiveness is therefore difficult to explain in terms of theories which attribute the emission essentially to excess Ba.

* G. E. Moore and H. W. Allison, Phys. Rev. 77, 246 (1950).

B4. Diffusion Phenomena in the Oxide Cathode. E. S. Rittner, *Philips Laboratories, Inc.*—Thermochemical calculations indicate that the equilibrium pressure of barium (and strontium) produced by reaction between the activator metal and (Ba-Sr)O is sufficiently high so that the rate of reaction is limited by the diffusion rate of the activator in the core nickel.[1] Similarly, the equilibrium pressure of the dissolved barium above the oxide is high enough so that the rate of barium depletion during the life of the cathode is limited by the rate of diffusion of barium out of the oxide. A theoretical survey of diffusion phenomena in the oxide cathode based upon recently determined diffusion coefficients[2,3] has yielded the following additional information. The activator-oxide reaction goes to completion in the very early stages of the activation schedule. The barium vapor so generated is transported throughout the porus oxide mass by means of Knudsen flow. During the activation period barium can penetrate into the oxide crystals for a distance of only a few microns. The subsequent slow diffusion of barium out of the oxide at operating temperatures accounts for the long life of the cathode.

[1] M.I.T. Conference Report on Physical Electronics, March 29, 1951, p. 24.

[2] G. F. Rouse and R. Forman, Phys. Rev. 82, 574 (1951); private communication.

[3] R. W. Redington, Phys. Rev. 82, 574 (1951).

B5. The Solubility and Diffusion Coefficient of Carbon in Nickel. J. J. Lander, H. E. Kern, and A. L. Beach, *Bell Telephone Laboratories.*—The weight percent solubility of carbon in nickel varies from 0.041 at 780°C to 0.245 at 1030°C. These results were obtained from carbon saturated 499 nickel sheet analyzed according to the method developed by L. A. Wooten and W. G. Guldner.

Values obtained for the diffusion coefficient of carbon in nickel range from 4.0×10^{-9} cm^2 per sec at 727°C to 4.1×10^{-7} at 1020°C. These values were obtained by a novel method in which carbon coated on one side of a nickel disk is diffused through the disk to react with nickel oxide coated on the other. Rates of diffusion are observed as rates of evolution of the gaseous products of reaction. The initial, steady, and final states predicted by diffusion theory may be accurately observed if proper experimental conditions are satisfied. The results have been applied in an analysis of reactions taking place in oxide coated thermionic cathodes. It was found in experiments with nickel coated on one side with BaO and on the other with C that rates of reaction between C and BaO were nearly identical with those between NiO and C. Thus the rate limiting factor in the reactions is the diffusion of carbon through nickel.

B6. The Electronic Properties of Barium Sulfide.* W. Grattidge† and H. John, *University of Missouri.*—Barium sulfide has been prepared as a cathode emitter and in the form of compressed pills. It has a work function of 2.1 ev with a wide variation possible in activation. The most active materials had an emission at temperatures of 900°K and greater, comparable to that from pure BaO. Pure nickel and platinum were used as base metals. An equimolar solid solution of $BaS-S+S$ had a work function of 2.6 ev. The electrical conductivity of BaS depended on the degree of activation and the denseness of the specimen but was much less than for BaO. At 1000°K the specific conductivity of a compressed pill was 10^{-5} ohm^{-1} cm^{-1}. The thermoelectric power was constant with temperature, decreasing with increasing activity, the warmer electrode always positive. Pure BaS had a thermoelectric power of 2.5 mv per degree between 700 and 1000°C. The effect of added impurities of iron was studied. Mass-spectrometer studies indicated a vapor pressure of the sulfide about one hundred times less than that of the oxide. The latent heat of vaporization was 104 kcal/mole.

* Supported in part by the ONR.

† Now at Massachusetts Institute of Technology, Cambridge, Massachusetts.

C1. The Use of Radioactive Isotopes in the Study of the Evaporation from Thermionic Cathodes.* W. F. Leverton and W. G. Shepherd, *University of Minnesota.*—The quantity of the alkaline earths transferred from oxide coated cathodes during processing and life has been measured. Radioactive tracer techniques are used. The isotopes Ba140, Sr89, and Ca45 are incorporated singly into carbonate cathode coating mixtures. The radioactive cathodes are used in diodes having a movable electrode which shields the anode from the cathode during all or any desired part of the tube processing schedule. At the conclusion of the test the diode is opened and the radioactivity on the anode, movable shield, and cathode is measured. This method has proven very useful in determining evaporation rates for Ba, Sr, and Ca as a function of cathode operating temperature, emission current, processing schedule, and life. Experiments are in progress to study the behavior of the double carbonate of Ba and Sr and the single carbonates of Ba, Sr, and Ca.

The tracer technique allows the detection and accurate measurements of quantities of cathode Ba, Sr, and Ca as small as 10^{-10} g.

* This work was supported by Signal Corps contract.

C2. Photoelectric Emission from BaO in an Accelerating Field. Paul E. Carroll* and E. A. Coomes, *University of Notre Dame.*—A consideration of the field dependent photoelectric effect reveals a convenient method for determining work functions of photoelectric emitters. By extending Fowler's photoelectric theory for a lowering of the potential barrier at the surface of the emitter due to the Schottky effect, it can be shown that the current should be proportional to the square root of the applied field for energies of input light a few tenths of an electron volt from the threshold. The slope of *I vs* $E^{1/2}$ is proportional to the work function. Nine independent determinations of the work function of a BaO cathode using this method are in agreement to within one percent. This method has the advantage over the use of Fowler plots in that a normalization to unit intensity of input light is not required. In general, the results on BaO are in qualitative agreement with the Guth-Mullin theory for photoemission in an accelerating field. Indications are that the true field at the BaO cathode is several times greater than the geometrically computed field. This would substantiate the thermionic Schottky emission data for alkaline earth oxides reported in the literature.

* Now at the Sylvania Electric Products, Inc., Kew Gardens, New York.

C3. Photoconductivity Study of Activation of Barium Oxide. H. B. DeVore, *R.C.A. Laboratories.*—Photoconductivity studies have been made for barium oxide cathodes at various stages of thermionic activation, for the purpose of attempting to establish the donor energy levels. Changes occurring during activation are reflected in the development of the long wavelength tail of the photoconductivity curve. For states of low activity, this tail has a threshold in the neighborhood of 2.3 electron volts, and, with increasing thermionic activity, a second threshold at about 1.5 electron volts develops. The measurements are interpreted as indicating the development of donors at levels having these depths below the conduction band during the activation. Tentative explanations of the origin of these donors are advanced.

C4. The Luminescence of BaO.* Virgil L. Stout, *University of Missouri (now at Stanford Research Institute).*—The luminescence of BaO has been studied in an endeavor to correlate its luminescent and thermionic properties. BaO samples were prepared by heating $BaCO_3$ in a vacuum. The carbonate was sprayed with a binder on two types of cathode base metals. These sample cathodes were mounted in a vacuum tube designed so that thermionic emission studies were possible at temperatures up to 1000°K and luminescent measurements could be made at temperatures down to 90°K. Measurements were made of thermionic emission and luminescent intensity distribution both as a function of the state of thermionic activation, and as a function of temperature. Results of these measurements have been interpreted in terms of a conventional model for BaO involving both donor and acceptor type impurities. Luminescence mechanisms have been proposed for the luminescent bands at 345 mμ and at 465 mμ which vary as a function of thermionic activation. The temperature dependence of the 345 mμ band was associated with the temperature dependence of the mean free path of a positive hole. From this association, one is able to determine the characteristic temperature of the fluorescent material.

* This work was supported in part by the ONR.

C5. On the *I–V* Characteristics of the "*L*-Cathode." E. S. Rittner and R. H. Ahlert, *Philips Laboratories, Inc.*—Measurements of the *I–V* characteristics of a planar diode incorporating an *L*-cathode have been made in the temperature range 1150–1400°K and in the voltage range 0–1500v. The data were taken with the use of a circuit* of the type previously employed by Loosjes and Vink,[1] which periodically discharges an *RC* network across the diode. In our work the time constant of the network was 60 μsec and the pulse repetition rate was 60 per second. The results are in accord with theoretical expectations in both the space charge and Schottky regions. Typical parameters obtained from a zero field Richardson plot are $\phi = 1.7$ ev, $A = 3.0$ amperes/cm^2 deg^2. Some observations regarding poisoning phenomena will also be reported.

* We are indebted to T. R. Kohler for the specific design employed.

[1] R. Loosjes and H. J. Vink, Philips Research Reports 2, 190 (1947).

C6. Physical Processes in the "*L*" Cathode. D. L. Shaefer and J. E. White, *General Electric Company.*—Experiments have been carried out to investigate further the nature of this emitter, whose mechanism has been discussed in a previous paper.[1] The pattern described by duPre and Rittner agrees in general with the results of the present work. Evidence has been accumulated to show that barium is delivered to the surface of such a cathode by surface diffusion and that the streaming of vapor from the pores is negligible.

In looking toward means of combating excessive barium evaporation, it was important to establish whether less or more than a monolayer of barium resides on the surface during operation. Two independent approaches have established that less than a monolayer exists in equilibrium under normal operating conditions. The evaporation rate of active material has been measured as a function of temperature and is compared with values for other commonly used thermionic emitters. The evaporant has been identified as barium metal.

[1] F. K. duPre and E. S. Rittner, Phys. Rev. 82, 573 (1951).

W. G. Shepherd presiding

ThO_2, Secondary Emission

D1. Electrolysis of Thorium Dioxide. I. Oxygen Evolution from Operating Cathodes. Edward Shapiro, *Bartol Research Foundation.*

D2. Electrolysis of Thorium Dioxide. II. Observations with Homogeneous Crystalline Specimens. W. E. Danforth, *Bartol Research Foundation.*

D3. The Angular Distribution of Secondary Electrons from Nickel. J. L. H. Jonker (Presented by F. K. duPre), *Philips Gloeielampenfabrieken.*—The common equipment for measuring secondary emission (disk-shaped or spherical electrode within a sphere) is not suitable for obtaining data about the angular distribution of secondary electrons. An electrode system with two concentric spheres was constructed in order to obtain a really radial retarding field with which the behavior of the secondary electrons with different velocities could be studied. The angular distribution of three groups of secondary electrons, slow genuine secondary electrons, secondary electrons with moderate velocities, and rapid reflected electrons, was measured as a function of the angle of incidence and of the energy of the primary electrons. The experimental results may be understood assuming Whiddington's law concerning the energy loss of electrons that penetrate into a solid substance, an isotropic distribution of the secondaries within the substance and an exponential absorption on their way out.

D4. Secondary Electron Emission from Germanium. J. B. Johnson and K. G. McKay, *Bell Telephone Laboratories.*—Secondary emission by electron bombardment has been measured for single crystals of Ge having a $p-n$ junction. The highly purified Ge was in one case doped with Ga for the p-type end, and in the other case heavily doped with Sb for the n-type end and with additional Ga for the p-type end. The carrier densities far from the junctions ranged from 2×10^{14}/cm^3 to 10^{17}/cm^3. The crystals were cut and polished along a (100) plane, chemically etched to give a clean surface, and given prolonged heat treatment up to 700°C in high vacuum during preparation of the tube. The two crystals, or the n- and p-halves of the same crystal face with the same treatment, show no difference in yield as large as 2 percent in spite of the difference in calculated surface fields. The yield curve in the range $V_p = 50$–5000 volts is very similar to that of Keller and Burgess,* having a $\delta_{max} = 1.1_5$ at 600 volts. Normalized energy distribution of secondaries shows no change over

$V_p = 500$–5000 volts, with most probable energy at 1.5–2.0 volts, and is the same on the p and n sides of both crystals. At 600°C δ is about 2 percent lower than at room temperature.

* R. L. Koller and J. S. Burgess, Phys. Rev. **70**, 571 (1946).

D5. Decay Time of Secondary Electron Emission. R. R. LAW, *R.C.A. Laboratories.*—Tests on a series of developmental tubes using multi-stage electrostatic electron multipliers show unexpectedly poor performance at high frequencies. The efficiency of a Class-C power amplifier with a five-stage multiplier is found to decrease with frequency from 0.7 at 50 mc to 0.2 at 450 mc. This result is obtained with both large-scale and small-scale tubes (over-all transit times of 2×10^{-9} and 5×10^{-10} second, respectively) with different input systems and with different dynode surfaces. The high frequency performance is substantially independent of voltage, temperature, current density, modulation index, or dynode material. The dynode materials so far tested include MgO, BaO, BeO, and gold.

These results may be explained by assuming that each stage of the electron multiplier exhibits a simple expotential decay characteristic with a time constant of 3×10^{-10} second. In view of the reproducibility of the effect with different tube structures, this time constant cannot reasonably be ascribed to circuit difficulties or known defects of electron multipliers. It is suggested that the secondary electron emission process itself introduces this characteristic; that is, that the fundamental process of secondary electron emission has a simple exponential decay characteristic with a time constant of about 3×10^{-10} second.

D6. The Wave-Mechanical Foundation of Baroody's Theory of Secondary Emission.* A. J. DEKKER† AND A. VAN DER ZIEL, *University of Minnesota.*—Baroody's semiclassical theory[1] of secondary emission can be derived with the help of wave mechanics. It can be shown that those collision processes between primary electrons and lattice electrons in which the lattice does not take up momentum give Baroody's results. The collision processes in which the lattice does take up momentum have been studies by Wooldridge[2] and have been applied to the problem of secondary emission. A closer inspection of the formulas shows, however, that for energies below 1000 volts these processes are less probable than those in which the lattice does not take up momentum. Consequently Baroody's theory of secondary emission might be essentially correct for moderately high primary energies. The theory can be extended by taking into account the motion of the lattice electrons. The probability of an energy loss between ΔE and $\Delta E+dE$, the probability of making a secondary electron with an energy between E and $E+dE$ and the total energy loss per unit path length are calculated.

* This work was supported by Signal Corps contract.

† Now at the University of British Columbia, Vancouver, Canada.

[1] E. M. Baroody, Phys. Rev. **78**, 780 (1950).

[2] D. E. Wooldridge, Phys. Rev. **56**, 562 (1939).

D7. Secondary Electron Emission under High Energy Electron Bombardment.* B. L. MILLER AND W. C. PORTER, *Bartol Research Foundation.*—Using a linear accelerator providing pulsed electrons up to 1.5 Mev, the secondary emission of various metals has been investigated over the range 20 kilovolts to 1.5 Mev. The metals studied have been gold, tungsten, silver, stainless steel, and beryllium and the work is continuing with other metals and a few insulating materials. Comparison with the work of Trump and Van de Graaff[1] over the region 50 to 300 kilovolts, and with results obtained at the Laboratory of Nuclear Science and Engineering, M.I.T.[2] in the region 1.0 to 1.5 Mev shows qualitative agreement.

* Assisted by the joint program of the ONR and AEC.

[1] J. G. Trump and R. J. Van de Graaff, Phys. Rev. **75**, 44 (1949).

[2] Progress Report, January 1, 1951.

D8. Back-Scattering of Low Energy Electrons. E. J. STERNGLASS, S. C. FREY, AND F. H. GRANNIS, *U. S. Naval Ordnance Laboratory.*—The energy dependence of electron back-scattering has been studied for carbon, copper, and molybdenum in the energy range from 0.2 to 2 kv which is of importance in the theory of secondary emission.[1] The undesirable effects of multiple scattering and secondary emission from the collector were greatly reduced by the use of spherical geometry and a suppressor screen of 68 percent open area coated with Aquadag. Appreciable backscattering was found to exist down to the lowest energies for all three elements, contrary to the expectations of some authors.[2] For an amorphous carbon film, the relative number of backscattered electrons of energy greater than 50 ev, η, was found to be essentially constant and equal to 0.07 ± 0.01. Similarly, the value for copper was found to be equal to 0.26 ± 0.02 over the whole range, in agreement with the value of 0.27 obtained by Gimpel and Richardson at 10 volts,[3] and 0.28 at 2 kv given by Palluel. For molybdenum, however, an increase of η from a value of 0.14 at 150 volts to 0.26 ± 0.02 at 1850 volts was observed. Since the data of Palluel show an increase of η with energy above 2 kv for all elements of $Z \gtrsim 30$, it appears that screening and binding energy considerations play an important role in the backscattering for the heavier elements.

[1] E. J. Sternglass, Phys. Rev. **80**, 925 (1950); thesis, Cornell University, February, 1951.

[2] P. Palluel, Compt. rend. **224**, 1492, 1551 (1947).

[3] I. Gimpel and O. Richardson, Proc. Roy. Soc. (London) **A182**, 17 (1943).

J. G. BUCK presiding

Field Emission

E1. Use of Field Emission in the Study of the Absorption of Ba on W. J. A. BECKER, *Bell Telephone Laboratories.*—The field emission electron microscope permits on to measure the intensity of emission from all crystallographic planes of W as functions of θ, T, and F: θ = fraction of surface covered with Ba, T = treatment temperature, F = applied field. From this one deduces how the Ba distributes itself over the surface, the ease with which it migrates on various planes, and the factors that determine evaporation rates. For θ from 0 to 1.0, the emission comes largely from Ba clusters with diameters ranging from 40 to 200A. These clusters form at or near 300°K and disappear at temperatures ranging from 370°K for 110 planes to 1000°K on 100 planes. Before the clusters disappear they are violently agitated. Above 800°K, Ba migrates quite freely everywhere. Between 1050 and 1600°K Ba evaporates; the rate depends on θ, T, and the plane. The ease of migration and the planes on which the Ba tends to congregate can be altered by the applied field. For $\theta > 1$ migration is even more pronounced; crystallites with diameters from 200 to 600A form and grow outward from the surface. They thus produce high local fields and hence local enhanced emission.

E2. Field Emission; A Comparison Between Theory and Experiment Including Pulsed Emission at Large Densities.* W. P. DYKE AND J. K. TROLAN, *Linfield College.*—Field emission from the hemispherical single crystal tungsten emitter was obtained with pulse techniques. The empirical current-voltage relationship was confirmed in the extended range of currents from 10^{-1} to 10^{-10} ampere. The distribution of current density over the emitting surface was obtained from the densitometric analysis of the simultaneous photograph of the emission pattern when the discharge took place in a modified Müller projection tube. Experimental current densities were in good agreement with those predicted by the wave-mechanical theory when Nichol's values for the work functions of several crystal directions for clean tungsten were used. Average values of the current density, obtained from the ratio of fractional current and fractional area in the constant field region, agreed with values predicted by the theory when the average value of the work function, $\phi=4.5$ ev was used. Current densities of the order of 10^{-1} ampere/cm^2 were observed. The experimental error was largely determined by the exponent $\phi^{3/2}/F$, where F is the electric field, and this exponent was known within 16 percent for direct currents and 20 percent for pulse measurements. Vacuum arcs occurred at current densities greater than those reported.

* This work was supported by the ONR and by Research Corporation. A part of the data analysis was supported by the Microwave Laboratory of the University of California at Berkeley.

E3. Ejection of Electrons from Molybdenum by Helium Ions. H. D. HAGSTRUM, *Bell Telephone Laboratories*.—The ejection of electrons from molybdenum by the ions He^+, He^{++}, and He_2^+ has been studied. Ion kinetic energies at the target surface have been varied from 10 to 1000 electron volts. The value of the parameter γ_i (number of electrons ejected per positive ion) for each ion is found to be remarkably insensitive to the kinetic energy of the ion. γ_i (He^+) is of order 0.3, γ_i (He^{++}) of order 0.95 for clean Mo in this range. The distribution in energy of ejected electrons has also been measured. Each of these data has been obtained for clean Mo and for Mo having a monolayer of gas absorbed upon it. Variation of γ_i with formation of the monolayer has been observed. Discussion of this work in the light of other experimental work and the theory of the ejection mechanism will be presented.

E4. An Interpretation of Periodic Deviation Data for Highly Refractory Metals. E. A. COOMES, *University of Notre Dame*.—Thermionic periodic deviation data for tantalum,[1] tungsten,[2] and molybdenum[3] filaments, with clean surfaces and with monomolecular contaminations have been examined in terms of the λ- and μ-coefficients of Herring and Nichols.[4] There is fair agreement between experiment and theory for λ for the box model with a mirror image barrier. This is interpreted as indicating that a monomolecular film, either electropositive or electronegative, did not introduce a peak in the potential barrier near the surface of the composite emitter. The main effect was to lower the work function and at the same time maintain an approximate mirror image configuration. The data from these experiments do not seem to substantiate the μ-coefficient for the box model.

[1] Munick, LaBerge, and Coomes, Phys. Rev. **80**, 887 (1950).
[2] A. L. Houde, C. S. B., Ph.D. thesis, University of Notre Dame.
[3] E. G. Brock, Ph.D. thesis, University of Notre Dame.
[4] C. Herring and M. H. Nicols, Revs. Modern Phys. **21**, 185 (1949).

E5. Arcing at Electrical Contacts on Closure. Part III. Development of the Arc.* L. H. GERMER AND J. L. SMITH, *Bell Telephone Laboratories*.—When two electrodes approach each other with a small difference of potential between them an arc may be struck before they touch. This arc is initiated by field emission electrons. After the first electrons there is a lapse of time, ranging from less than 0.002 to about 0.05×10^{-6} sec, during which the arc is becoming established. For this transition time the potential between the electrodes decreases from the applied voltage to a final steady value arc voltage which is independent of current and characteristic of the metal of the electrodes. The transition depends in striking fashion upon the cleanness of the electrode surfaces but there are also erratic variations from one experiment to another; the decrease in potential is, furthermore, sometimes at a fairly steady rate but in other experiments there are irregular upward fluctuations. Oscilloscopic study of this variation of potential seems to furnish the best experimental method for investigation of the way in which an arc develops. The oscilloscopic equipment gives satisfactory photographic reproductions of single closures with a time resolution of about 0.001×10^{-6} sec. The equipment is of conventional design with only moderate modifications.

* Parts I and II, J. Appl. Phys. **22**, 955 (1951) and **22**, 1133 (1951).

E6. The Space Charge Suppression of Flicker Effect.* A VAN DER ZIEL, *University of Minnesota*.—Schottky's formula[1] for the Flicker noise in a diode under space charge conditions may be written:

$$\langle i_a^2\rangle=(g_m V_T/I_s)^2\langle i_s^2\rangle. \tag{1}$$

In this equation $\langle i_s^2\rangle$ is the fluctuation in the emission current I_s, $\langle i_a^2\rangle$ the fluctuation in the anode current I_a, g_m is the transconductance and $V_T=kT_c/e$, where T_c is the cathode temperature. Schottky's comparison of the space-charge suppression of Flicker noise *versus* shot noise is in error, however; the corresponding formula for shot noise is

$$\langle i_a^2\rangle=2\theta(g_m V_T/I_s)\langle i_s^2\rangle, \tag{2}$$

where $\theta=3(1-\pi/4)$. It can be shown from (1) that in those space charge limited triodes, in which the Flicker noise is due to a fluctuation in work function, the equivalent Flicker noise emf in the grid circuit of the tube is nearly equal to the fluctuation in work function. Consequently the best way of obtaining information about the fluctuating work function consists in measuring the noise resistance of space charge limited triodes as a function of frequency.

* This work was supported by Signal Corps contract.
[1] W. Schottky, Physica **4**, 175 (1937).

E7. Cold Emission of Electrons in Spark Gaps. F. LLEWELLYN JONES, *University of Wales*.—Pre-breakdown electron production, e.g., in spark gaps, is related to the time lag of sparking, and estimates of electron emission from the cathode can be made from analysis of time-lag data. In this way emission from various metal surfaces: Al, Ni, W, Fe, Cu, was measured in different gas atmospheres: dry and moist air and H_2. It was found that emission $i\simeq10^6$ electron/sec were obtainable for most metals in the atmosphere under microscopic fields $F\simeq10^5$ v/cm. Further, the rate of emission depended not only on the nature of the metal, but also upon its surface state, e.g., grinding a surface could increase i by a factor $\sim10^6$ compared with that from a polished surface. The relation between i and F was found to be $\ln(i/F^2)=A/F+B$, indicating that the extraction mechanism was a field process. The technique employed allowed effects of electron attachment and recombination to be demonstrated. In moist air, for example, post-breakdown ionization in a spark was removed after about 10^{-2} sec, while in dry air ions remained in the gap (0.025 cc) for times as long as 0.1 sec.

E8. Observations with the Field Emission Microscope. E. W. MÜLLER, *Kaiser Wilhelm Institut für Chemie.*