SEPTEMBER 1, 1940 PHYSICAL REVIEW VOLUME 58

The Characteristics and Function of Anode Spots in Glow Discharges*

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(Received January 5, 1940)

Brilliant hemispherical anode spots appeared on a small disk or spherical anode mounted at the center of a large copper spherical discharge chamber which served as cathode during an investigation of nitrogen glows. Such an arrangement permits large anode current densities with a normal cathode fall in potential. At a critical current density at the anode, the spots form and arrange themselves in beautiful geometrical patterns. In nitrogen the spots appeared only in the pressure range of 0.15 to 1.50 mm Hg. Space potentials, electron temperatures, electron and ion densities determined by a Langmuir probe analysis revealed that the spots are regions of intense ionization, and that the region just above them contains a net positive space charge. The potential fall through a spot is nearly equal to the first ionization potential of nitrogen. A method was developed for growing anode spots at will on a small disk probe mounted flush with the anode surface but insulated from it. The current-voltage characteristics for this probe, or auxiliary anode, exhibit peaks which account for the stability and size of the spots. An investigation of the current-voltage relationships of the entire discharge showed that anode spots occur chiefly in the region in which the current increases with small change in voltage. At sufficiently great current densities the spots move about because of the magnetic field accompanying the discharge. The function of the spots is to furnish the positive ions necessary for the maintenance of a stable discharge in the plasma extending from anode to negative glow and to aid in the collection of electrons at the anode. A mechanism for the formation of the spots as a combined space charge and bipolar current phenomenon is proposed.

INTRODUCTION

IN the course of some investigations of the general characteristics of glow discharges maintained between concentric spherical electrodes, an unexpected phenomenon appeared when the inner electrode was small and was made the anode. In a limited pressure range, and for the relatively large current densities available near the anode in this type of discharge chamber, the anode surface, instead of being coated with a uniform glow, became overlaid with a number of brilliant hemispherical spots. At times these were arranged in beautiful geometrical patterns of remarkable stability, while at other times they were in rapid motion. Their velocity could be accelerated or retarded by the application of an external magnetic field.

The appearance of these anode spots in a nitrogen glow at various pressures and current densities is shown in Fig. 1. In this gas the spots consist of two bright layers. The inner portion of the spots is salmon pink, while the outer layer is of a yellow-orange color. A faint luminous membrane of glow covers the region between the spots. A thin dark space exists between the spot and the anode itself. So long as the nitrogen was fairly pure, the spots were all of the same size at a given pressure. If the discharge was contaminated with air, the spots were always fewer in number, and not all of uniform size.

The pattern formed by the spots depends on the shape and size of the anode. The number of spots present increases, in general, with the current and pressure, but is influenced somewhat by the surface conditions of the anode. The size of individual spots increases as the gas pressure is reduced.

Although the observation of this phenomenon at first appeared to be a new discovery, a search of the literature revealed that it had been reported previously by other investigators. Apparently anode spots were first described by Lehmann[1] who found their occurrence in an air glow discharge, and were later reported by other workers[2-5] for several other gases. Thomas and Duffendack found the spots present in pure H_2, N_2, CO, and mixtures of these diatomic gases with various noble gases, but could not produce

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* Presented at the meeting of the American Physical Society, San Diego, California, June 22–24, 1938; Palo Alto, California, June 28–July 1, 1939.

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[1] O. Lehmann, Ann. d. Physik **7**, 1 (1902).

[2] G. M. J. MacKaye, Phys. Rev. **15**, 309 (1920).

[3] C. H. Thomas and O. S. Duffendack, Phys. Rev. **35**, 72 (1930).

[4] E. Kiessling, Zeits. f. Physik **96**, 365 (1935).

[5] A. Guntherschultze, W. Bär and H. Betz, Zeits. f. Physik **109**, 293 (1938).

them either in O_2 or in pure noble gases in a discharge tube which had been carefully cleaned and outgassed.

In all these investigations only those characteristics of anode spots which could be observed visually were studied. Specifically, the influence of the nature of the gas and the electrodes, current density, pressure, and duration of the discharge on the pattern, number, size, motion and permanence of the spots were investigated. No attempt was made either to correlate the occurrence of the spots with the general circuit characteristics of the discharge or to study the electrical properties of the individual spots.

The researches described in the present paper were performed in order to acquire quantitative information about the physical conditions associated with anode spots which might possibly lead to a better understanding of the processes which occur in their formation as well as their function in the maintenance of a stable discharge.

Method of Investigation

The Langmuir dynamic method of probe analysis permits the determination of the space potentials, electron temperatures, and densities of electrons and positive ions in those regions of a discharge known as a plasma.[3–8] Since a map of these quantities provides the most information at present obtainable about the electrical structure of gaseous discharges, it was determined to make such an analysis of anode spots.

A preliminary attempt to investigate an anode spot occurring at the edge of a disk electrode in this way resulted in failure as the spot was repelled by the probe. A method was developed for growing and anchoring a spot on a small auxiliary electrode mounted flush with the surface of the anode but insulated from it. This permitted a probe analysis of the region surrounding a spot so formed and anchored.

A study was made of the current-voltage characteristics of the auxiliary electrode during the growth of spots upon it. The information so obtained provides a possible explanation of the remarkable stability of the anode spots and their function in maintaining a stable discharge.

Finally, the external circuit characteristics of nitrogen glows maintained in the spherical discharge chamber were studied. This was done to reveal any relationship existing between these circuit characteristics and the occurrence of anode spots.

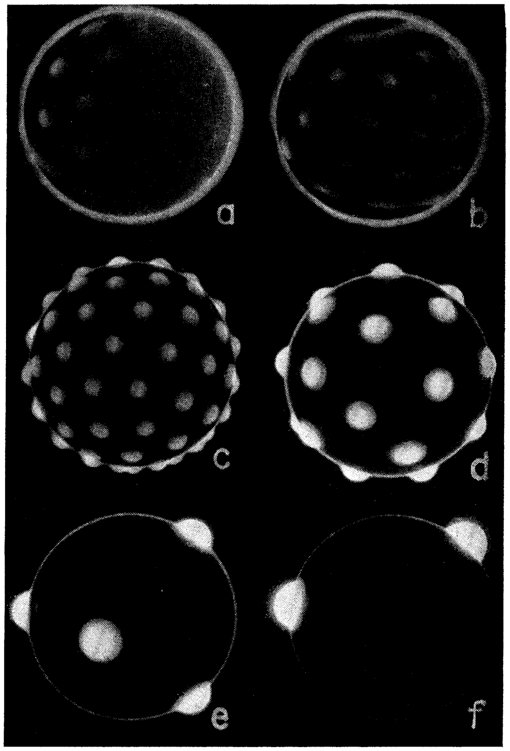

FIG. 1. Anode spots on a spherical anode. (a) Pressure 1.25 mm Hg, current 420 ma; (b) 1.20 mm Hg, 420 ma; (c) 0.79 mm Hg, 425 ma; (d) 0.41 mm Hg, 465 ma; (e) 0.36 mm Hg, 390 ma; (f) 0.26 mm Hg, 400 ma.

Apparatus

The discharge chamber in which these investigations were made was primarily designed for the purpose of studying glow discharges between spherical electrodes. It was admirably suited to these researches, since it provided a very large cathode area (708 sq. cm) which permitted the attainment of very large values of drift current for a normal cathode fall of potential. This permitted far greater current densities at the anode than were attainable in former investigations. The parasitic charging of insulating

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[6] I. Langmuir and H. Mott-Smith, Jr., Gen. Elec. Rev. **27**, 449 (1924).

[7] H. Mott-Smith, Jr., and I. Langmuir, Phys. Rev. **28**, 727 (1926).

[8] I. Langmuir and H. Mott-Smith, Jr., Gen. Elec. Rev. **27**, 767 (1924)

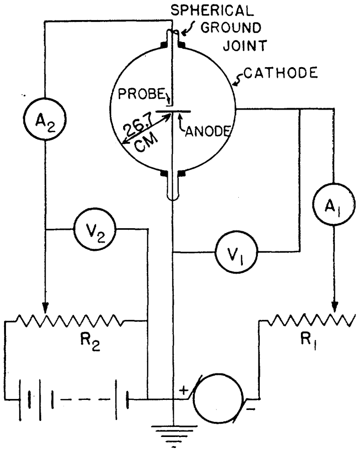

FIG. 2. Discharge chamber and circuit diagram.

surfaces due to the diffusion of ions and electrons to them was practically eliminated by the nature of the apparatus itself. This feature made the discharge currents which are ordinarily considered to be unsteady, very steady, and contributed greatly to the reliability and success of the experiments.

The discharge chamber and the circuit are shown schematically in Fig. 2. The chamber consists of two spun flanged copper hemispheres clamped together between steel rings with "*C*" clamps. A ring of fuse wire, clamped between the flanges, effected an airtight seal. The anode which was a copper sphere, 5.1 cm in diameter, or a circular disk mounted concentrically with the outer sphere was supported by a rod or tube of copper insulated from the discharge with a sheath of Pyrex tubing.

The circuit is shown diagrammatically in this figure. The potential difference for maintaining the discharge was supplied by a 1500-volt d.c. generator. The series ballast resistance, R_1, a rheostat having a maximum value of 21,400 ohms, was always kept in the circuit to assure stability.

The probe used to study the spots was a cylinder of tungsten wire 0.5 cm long, and 0.013 cm in diameter. This probe was fastened with a braid of fine copper wire to a windlass which was turned through a conical ground glass joint at the top of the probe tower. The probe tower was mounted on the spherical or "ball and socket" ground glass joint which permitted an angular displacement from the axis of the probe tower as well as a rotation of the probe about it.[9] With this arrangement any of the region above the anode or to the side of it contained within the frustrum of a limiting cone could be explored with great facility and precision of adjustment. This probe was used to investigate the plasma which surrounds the spots.

These experiments were performed in fairly pure, dry nitrogen which was used for several reasons. Brilliant spots of great stability formed in it quite readily in a very convenient pressure range and with good reproducibility of results. If air should leak into the chamber or be released from the walls the purity is not changed greatly since the oxygen cleans up and combines with the cathode surface after a few hours of running. The gas was obtained from a tank of commercially pure nitrogen and was slowly passed through a liquid-oxygen trap into a reservoir which had previously been evacuated with a 2-stage mercury diffusion pump and flushed several times. It was released from this into the discharge chamber as needed through another trap which was kept at all times in a slush of dry ice and acetone.

ANODE SPOTS ON A SPHERICAL ELECTRODE

When the anode was a copper sphere, it was coated with a uniform glow at all pressures exceeding 1.50 mm Hg and for drift current values not greater than 500 ma. If the pressure was increased or the current decreased so that the anode was not saturated with glow, the luminous region adjoining the anode grew thicker and more diffuse. For nitrogen discharges, anode spots never occurred at pressures exceeding 1.50 mm Hg for the current densities available.

At a pressure of 1.25 mm Hg and a drift current of 420 ma some spots appeared on the part of the anode facing the cathode glow as shown in Fig. 1a. At this pressure, if the current is increased, the spots move about so rapidly that the glow appears to be uniform once more. With the current constant and the pressure reduced to 1.20 mm Hg, some of the spots had an oscillatory motion, while others remained at rest as shown in Fig. 1b. As the pressure was further reduced the

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[9] S. M. Rubens and J. E. Henderson, Rev. Sci. Inst. **10**, 49 (1939).

spots increased in size and diminished in number until at 0.15 mm Hg only one large spot was present. These effects are illustrated in Fig. 1c, d, e, and f. Since the spots were more or less uniformly distributed over the surface of the sphere, somewhat more than half the total number of spots are visible in the photographs. The single spot occurring at 0.15 mm Hg was not in a convenient position for photography. At a given pressure, the spacing of the spots changes only slightly with the current regardless of the number present.

On a disk anode, the spots are evenly spaced in a ring about the edge of the disk. Even though the ring is not completely filled, the spacing seems to be fixed for spots of a given size. If both faces of the disk are exposed to the discharge so that there is a ring of spots on each face of the anode, the positions of the spots on one face are between those on the other.

PROBE ANALYSIS OF AN ANCHORED SPOT

When the cylindrical probe was used for exploring the discharge in the vicinity of a spot formed at the edge of the disk anode, data were obtained which were valid for determining the space potentials, electron temperatures and ion densities. However, when it was attempted to penetrate the spot with the probe, the spot was repelled so long as the probe potential was sufficiently negative for it to collect positive ions. In fact, it was not possible to penetrate the surface of a spot with the probe unless its potential was 15 volts or more positive with respect to the anode. If the probe was placed between two spots, and if its potential was raised to a positive value in excess of 15 volts, a spot formed which enveloped the probe wire and rested on the anode. This occurred so long as the probe was not more than a few millimeters distant from the anode regardless of its position relative to the center of the anode. In appearance and behavior a spot so formed resembled those which occurred spontaneously at the edge of the anode. If the probe was moved, this glowing spot moved with it, and when it approached one of the spots already present at the rim of the anode, the spots repelled one another. Evidently there is a repulsive interaction between the positive ion sheath surrounding the probe and the anode spots. Anode spots, therefore, must possess an intrinsically positive charge. All these effects suggested that a spot might be formed and anchored on a small auxiliary disk electrode mounted flush with the anode surface but insulated from it.

The construction of an anode having at its center an auxiliary anode or plane circular probe at the center is shown in Fig. 3. The auxiliary anode is a copper disk 0.60 cm in diameter and is insulated from the anode proper with a thin mica washer. The anode is a circular copper disk 8.00 cm in diameter and 0.275 cm thick.

When the disk probe was made sufficiently positive with respect to the anode, as expected, a spot, which exhibited all the characteristics of those which appeared spontaneously at the edge of the anode, formed on it. When this took place, the current to the plane probe increased discontinuously to several times its former value. In a nitrogen discharge, the potential to which the disk probe had to be raised in order to form a spot ranged from 0 to 10 volts depending on the pressure, total drift current, and the anode surface conditions. The manner in which the probe potential necessary to form the spot depended on the drift current when the pressure was held constant at 0.50 millimeter is shown in Fig. 4. If the current density was sufficiently great the spot occurred when the probe potential was zero, and if the current was further increased, the probe potential had to be made negative in order to remove the spot. This fact shows that for a given pressure of nitrogen a spot forms when the current density reaches a critical value.

Once the probe was made sufficiently positive to form a spot, reversing the potential of the

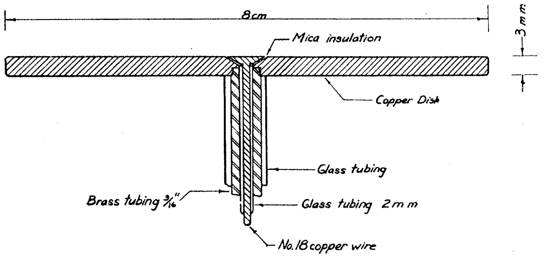

FIG. 3. Diagram showing construction of the anode having at its center an insulated circular disk probe or auxiliary anode upon which anode spots were grown.

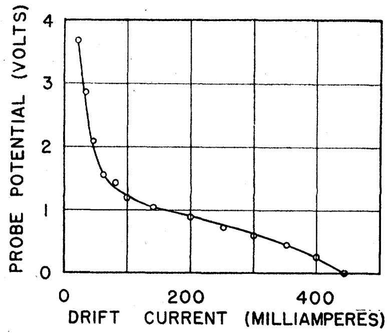

FIG. 4. Curve showing the variation with the drift current of the disk probe potential at which a spot forms in N_2 at 50 mm Hg pressure.

probe did not cause the spot to fade out if the drift current was greater than 100 milliamperes. Instead, the spot moved away from the plane probe as soon as the probe began to collect positive ions and came to rest between the plane probe and the edge of the anode where spots were already present. If the flat probe was again made positive, this spot did not return to the probe, but another spot formed which again moved away upon reversal of the probe potential. At drift currents of 300 ma or more, a continued repetition of this procedure resulted in the formation of a ring of spots between the center and the edge of the anode. As many as six equally spaced spots could be placed in this inner ring. As the spots moved away from the center toward the edge of the anode, they became more brilliant and more sharply defined. Simultaneous with this increase in number of spots an increase in the total drift current occurred.

At a pressure of 0.48 mm Hg and a drift current of 200 ma there was a very symmetrical distribution of spots around the edge of the disk anode. Ten spots rested on the upper surface and ten on the lower one in alternating positions. Under these conditions a spot which had a radius of about 0.5 cm was formed and anchored on the plane probe when its potential was 1.70 volts positive with respect to the anode.

After this spot was formed on the flat disk probe, the movable cylindrical probe was used to explore the region surrounding it. The axis of the probe wire was kept parallel to the anode surface in all the measurements which were along two lines normal to the anode surface, one passing through the center of the flat probe and the other displaced one centimeter from the center. Thus the first line passed through the upper surface of the spot, and the other was about 0.5 cm removed from the base of the spot.

The probe current-voltage characteristics were obtained in the usual manner by plotting the current collected by the probe against the probe potential. These plots were typical of cylindrical probe characteristic curves, and the Langmuir type of analysis permitted the electron temperature, T_e, the space potential, V_s, the positive ion density, N_p, and electron density, N_e, to be computed from them. Logarithmic plots of the electron currents against the probe potential were linear except in the vicinity of the space potential so that a Maxwellian distribution of electron velocities could be assumed.

The results listed in Table I were computed from the probe measurements made directly above the central spot while those in Table II resulted from the measurements taken to one side of it. In Fig. 5 the space potentials and electron temperatures are plotted for these two sets of data. The solid lines are for the measurements directly over the spot, whereas the broken lines represent points which are 1 cm displaced from the center of the anode; that is, to one side of the spot. The diagram below the graph indicates on the same scale the position of the points where the probe measurements were made. The dotted semicircle represents the observed boundary of the spot, and the numbers are the values measured from the anode of the space potential at each point. The shape of the full line curve marked V_s clearly indicates that the spot is a sheath, since the space potential rises rapidly as the boundary of the spot is approached. The

TABLE I. *Results of the probe analysis of the region directly above an anchored anode spot.*

DISTANCE FROM ANODE CM	T_e °K	V_s VOLTS	N_e ELECTRONS/CM³	N_p +IONS/CM³
0.40	26,600	11.2	6.64×10^7	7.3×10^9
0.53	23,200	12.0	8.90×10^7	5.3×10^9
0.70	11,600	15.5	1.10×10^8	4.0×10^9
0.80	11,600	16.0	1.17×10^8	4.0×10^9
1.00	11,500	17.0	1.52×10^8	3.8×10^9
1.50	12,100	17.6	1.66×10^8	2.8×10^9
2.40	12,100	18.0	1.59×10^8	2.5×10^9
3.50	11,000	18.5	1.46×10^8	2.2×10^9
4.50	11,100	18.7	1.52×10^8	1.7×10^9
5.50	10,100	18.8	1.46×10^8	1.6×10^9

closeness of the two° V_s curves at points more than 1 cm from the anode as well as the small slope in this region shows that the potential gradients are low. Tables I and II show that there are about ten times as many positive ions per cm^3 as electrons. As the spot is approached from directly above the positive ion density increases quite rapidly while the electron density decreases. On the other hand, the positive ion density decreases as the anode is approached to one side of the spot. These facts imply that the uppermost part of the spot and the region just above it contain a considerable net positive ion space charge. An examination of N_e and T_e in Table I shows that electrons are drawn from the plasma surrounding a spot by the spot itself. Evidently the spot serves as an efficient collector of electrons for the anode.

Further evidence of the existence of positive ion space charge in the outer layer of the spot comes from the examination of the probe characteristic representing measurements taken when the probe is 0.40 cm above the center of the anode. At this distance the probe actually caused severe distortion of the spot when its potential was sufficiently negative so that an extensive positive ion sheath surrounded it. The current-voltage characteristic taken 0.40 cm above the anode together with the one at 1 cm above the anode are shown in Fig. 6. Emeleus and Brown[10] have shown that presence of concave downward curvature in the positive ion branch of the characteristic near the floating potential is always indicative of the presence of positive space charge. This anomaly is clearly exhibited in the curve for 0.4 cm while the one taken at 1.0 cm above the anode is a normal characteristic. Thus, there is a small region near the upper surface of the spot which is densely populated with positive ions. This fact explains two things. First, it shows that the spots are an efficient region of positive ion generation. Second, it provides a plausible explanation for the symmetrical patterns formed by the spots, since the spots represent a net positive charge. The probe measurements indicate that the ionized gas in between the spots is a plasma, where the net space charge and potential gradients are small. Since the motion of the spots was influenced by external magnetic fields, and since the electron temperature increases markedly as the spot is approached, it may be assumed in agreement with Thomas and Duffendack that the spots consist of localized bipolar current beams. Two neighboring spots would then constitute portions of two localized parallel currents, and would attract each other if it were not for their associated positive space charge which repels electrostatically. A balance exists between the electrostatic repulsion of the localized space charge regions and the magnetic forces arising from the interaction of the current beams producing a stable pattern.

TABLE II. *Results of the probe analysis of the region 1 cm from the center and to the side of an anchored anode spot.*

DISTANCE FROM ANODE CM	T_e °K	V_s VOLTS	N_e ELECTRONS/CM^3	N_p +IONS/CM^3
0.50	11,700	16.5	1.15×10^8	1.34×10^9
1.00	12,100	17.4	1.74×10^8	2.08×10^9
2.00	10,600	18.7	1.74×10^8	2.55×10^9
3.00	10,600	18.8	1.58×10^8	2.38×10^9
4.00	11,600	19.2	1.58×10^8	2.19×10^9
5.00	10,800	19.3	1.58×10^8	1.76×10^9

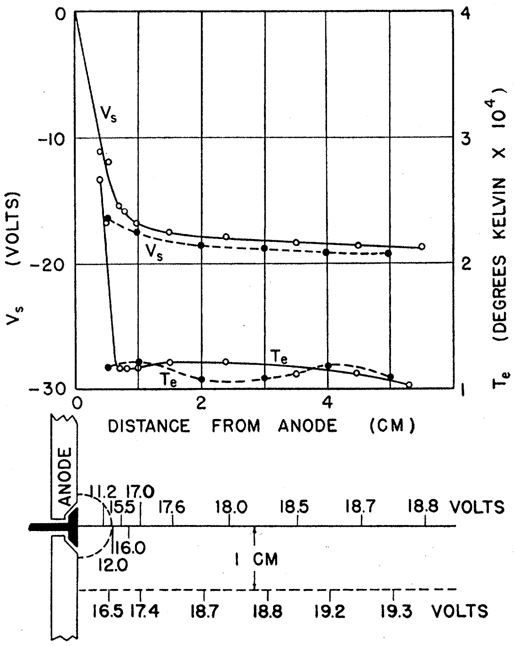

FIG. 5. Space potential and electron temperature distributions directly above and to one side of an anode spot formed on the disk probe or auxiliary anode.

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[10] K. G. Emeleus and W. L. Brown. Phil. Mag. **27**, 898 (1936).

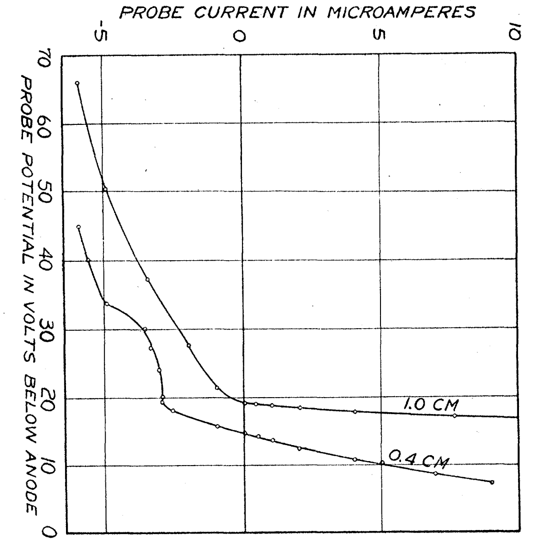

FIG. 6. Normal and anomalous cylindrical probe characteristics showing the effect of positive space charge as observed directly above an anode spot.

From the map of the space potentials, Fig. 5, the anode fall through the spot can be determined. The surface of the spot is an equipotential which is 14.0 volts negative with respect to the anode. The flat probe, on which the spot was anchored during these investigations, was 1.70 volts positive with respect to the anode. Thus the total potential fall through the spot is 15.7 volts. The normal anode fall should be at least equal to the first ionization potential of the gas.[11] The most recently accepted value of the first ionization potential of N_2 is 15.50 volts[12, 13] so that the agreement is excellent. The plasma just outside the surface of the spot contains electrons which have a Maxwellian velocity distribution associated with a temperature of about 23,000°K. Therefore, the average energy of the electrons at this point is $\frac{3}{2}KT_e$ or about 3.0 electron volts.

SPOT GROWTH CHARACTERISTICS

The auxiliary anode upon which the spots were formed and anchored was also used as a probe for investigating the current-voltage relationships for the discharge within the spot itself. If the potential of the plane probe is increased beyond the amount necessary to form a spot upon it, the spot at first increases in brilliance as the current to the probe increases. At a critical value of the probe potential the current reaches a sharp maximum from which it rapidly falls. The potential at which the current maximum occurs is definite and reproducible for a given drift current and pressure so long as the surface conditions of the probe do not change appreciably. At pressures of 0.15 mm Hg and less no maximum is present and the current increases continuously with the probe potential. This is the pressure at which only one spot forms on the anode for all current densities up to the maximum value allowed by the power supply. This effect is illustrated in Fig. 7 and Fig. 8.

In each case the spot forms at the discontinuity, increases in brilliance until the current maximum has been reached, and then rapidly dims and shrinks in size as the current decreases with increasing probe potential. After the current minimum has been reached, the spot again grows in size, exceeding the dimensions of the spots occurring at the edge, and becomes far more

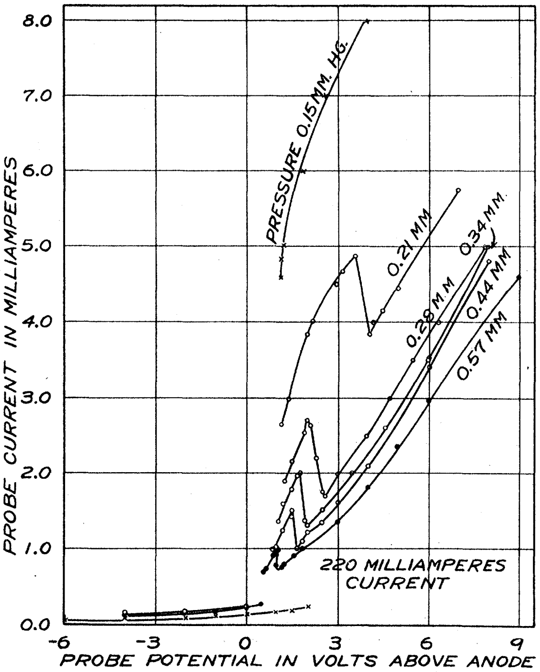

FIG. 7. Disk probe current-potential curves for the formation of a spot in N_2 at various pressures and constant drift current (220 ma).

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[11] A. von Engel and M. Steenbeck, *Electrische Gasentladungen*, Vol. 2, p. 93.

[12] R. E. Worley and F. A. Jenkins, Phys. Rev. **54**, 305 (1938).

[13] J. Kaplan, Phys. Rev. **55**, 111 (1939).

brilliant. At the current density corresponding to the maximum, the artificially grown spot is indistinguishable from those occurring naturally. Evidently the spots develop until this condition is reached. Since further development entails a smaller current to the spot as the maximum is passed and the general circuit conditions demand an increase in current, new spots form to meet this current increase rather than the continued growth of any one spot.

Circuit Characteristics for Discharges Which Include Anode Spots

Current-voltage characteristics of the spherical discharge chamber curves were obtained in a nitrogen glow for several different pressures. Figure 9 shows a set of curves obtained when the disk anode illustrated in Fig. 3 was employed at various pressures. Almost identical curves were obtained when a spherical anode 5.1 cm in diameter was used. In each case there is a portion where the currents are low and the voltage falls steeply with increasing current. Along this part of the curve the anode was not yet covered with glow, and what appeared to be a short positive column or possibly an extended sheath protruded from the anode. At two- or three-tenths of a mm Hg pressure, and at currents below 10 milliamperes, the positive column became striated, the number of striations decreasing as the current was increased. At higher pressure values the positive column was uniform. In any case, whenever a positive column was present, the cathode glow appeared as a small circular patch of light, no larger than the anode so that the discharge path was a narrow tubular region connecting the anode to the cathode glow. When the current density was enhanced, the glow at the cathode was spread over a greater area, and at a critical current density a well-defined anode glow replaced the positive column. This critical current density occurs where the steeply falling portion of the characteristic breaks into the flat portion.

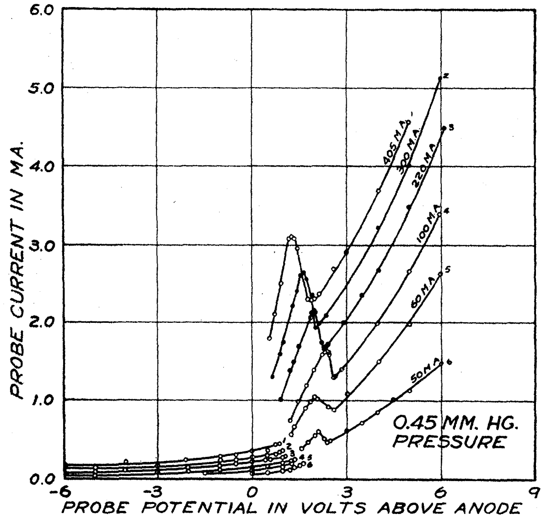

Fig. 8. Disk probe current-potential curves for the formation of a spot in N_2 at various drift currents and constant pressure (0.45 mm Hg).

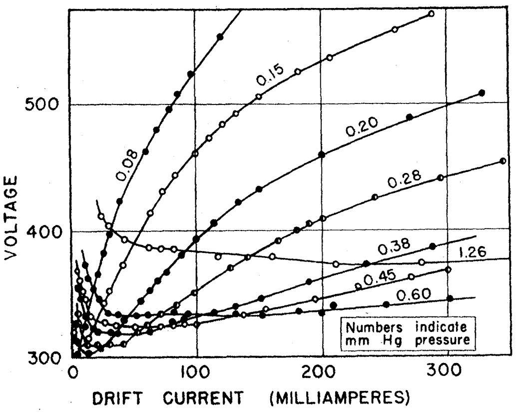

Fig. 9. Characteristic current-voltage curves at various pressures for an N_2 glow discharge with a large circular disk as anode.

In each case the voltage fell to a small but rather sharp minimum just as the anode became covered with glow and then leveled off to a rather long flat or gently rising portion. The shape of these curves is quite reproducible, but their position along the voltage axis depends to a large extent on the surface conditions of the anode as well as the position of the cathode glow on the outer sphere. At the higher pressures the cathode was never saturated and the small irregular patch of cathode glow appeared at different positions depending upon the discharge path during ignition. The size of the generator limited the current to 500 milliamperes.

The spots first appear at the beginning of the transition from the steeply falling to the flat branch of the curve, and increase in number until a complete ring of evenly spaced spots has formed around the edge of the disk. It is seen that the length of the flat portion of the curves increases with the pressure, and this flat portion of the characteristic curve is also directly related to the number of spots present. In fact, the spots undoubtedly furnish the mechanism for increasing the current with practically no change in the total voltage drop across the chamber.

At a given pressure the number of spots increased with increasing current so long as the pressure was greater than 0.15 mm Hg. At pressures of 0.40 mm Hg and above, this occurred along the flat and rising portions of the current-voltage curves, but at pressures below 0.40 mm only along the rising portion. For large current values the spots were usually in rapid motion and the voltage increased but very little. Sometimes the pattern of spots as a whole rotated with a constant velocity, while at other times some of the spots remained at rest while others moved about. If an external magnetic field was applied, this motion could be increased, stopped, or even reversed. From these observations, it may be concluded in agreement with Thomas and Duffendack that the spots consist of individual current beams and that their motion is due to the interaction of the magnetic field which accompanies these beams with other magnetic fields that may be present.

At 0.15 mm of mercury pressure there is a fairly narrow minimum but no flat portion for the curve. It is at this pressure that only one large spot occurs. This single spot increased in size as the current was increased and suddenly changed over into a uniform whitish glow on the rising portion of the curve. A further increase in current caused the glow to become thinner and brighter. At a critical current value, the glow disappeared entirely, the entire chamber being filled with a faint luminosity. At about 0.10 mm Hg pressure, the spot having grown in size, suddenly collapsed and a uniform glow enveloped the anode. A further decrease in pressure or increase in current causes this glow to shrink in thickness and increase in brilliance. As the pressure is still further reduced, the minimum becomes more narrow, and the falling branch becomes shorter until at a pressure of 0.05 mm Hg there is only a rising curve. This type of characteristic does not accompany the formation of anode spots at all.

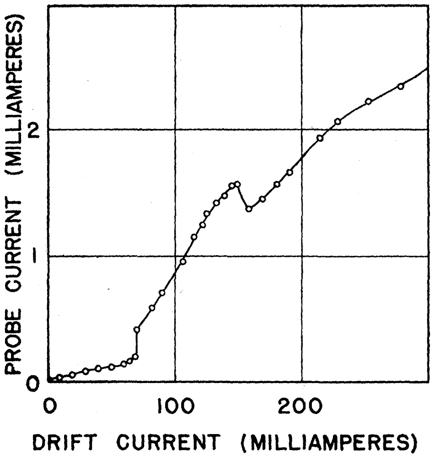

FIG. 10. Curve showing the variation of the disk-probe current with the total drift current at 0.44 mm Hg pressure when the probe is maintained at the anode potential so that a spot forms spontaneously upon it.

In order to see if the current peaks which are so clearly exhibited in the probe current-potential curves have any counterpart in the spots which appear on the anode spontaneously, the probe potential was maintained at that of the anode, and the probe current was recorded as the drift current in the discharge was varied. The results are shown in Fig. 10.

Two peaks are clearly present when the drift current is varied rapidly, but when its value is changed slowly enough so that the data could be recorded, the first peak was reduced to a short plateau. The rapid rise in probe current at about 70 ma drift current was accompanied by the appearance of a diffuse spot which covered the probe. As the drift current was increased, the spot grew brighter and became more sharply defined. When the peak at 150 ma was passed, the spot became less bright and its size was lessened just as was the case of the spots which were formed by altering the probe potential. Simultaneously, another spot appeared at the edge of the anode just as the current peak was passed.

The fact that a spot appears when the flat probe collects a definite current, and that as the total drift current is increased, the probe current passes through a peak even though the surface of the probe is at the anode potential, is further evidence that the spots formed by altering the probe potential are of the same nature as those which are formed spontaneously.

SUMMARY OF THE EXPERIMENTAL RESULTS

The following are the more important conclusions that may be drawn from these investigations regarding anode spots: Anode spots occur in glow discharges when the current density at the anode becomes sufficiently great. They are regions of intense ionization, consisting of electron beams flowing into the region, toward the anode, and positive ions flowing out, toward the cathode. The spots are regions which possess a net positive charge and are bounded by a plasma. The mutual repulsion of these positive space charges combined with the magnetic attraction of parallel ion beams gives rise to the stable spot patterns. Their size is determined by the pressure, and is larger the lower the pressure. The electrons from the plasma gain energy rapidly as they approach the spot.

The current-voltage characteristic curves are almost flat in the region in which spots occur, there being a slight increase in voltage for a large change in current. The potential drop through a spot is approximately the first ionization potential of the gas in the tube and corresponds well with the normal anode fall. The spots serve to furnish the additional positive ions necessary to keep the discharge stable as the current increases, and to collect electrons from this plasma which surrounds them. The current-voltage characteristic of an individual spot possesses a sharp maximum. The normal condition of a spot is the current density corresponding to this maximum. Since a further increase in voltage results in a current decrease, a new spot tends to form resulting in many spots instead of one large one.

THE MECHANISM OF ANODE SPOTS

The data accumulated in these researches are adequate for postulating a mechanism which explains the stability of anode spots as a combined space charge and bipolar current beam phenomenon. As the gradients are low in the discharge except for the anode and cathode fall, the only place where positive ions can be generated and still serve their function in the plasma is in the anode fall. From the flat characteristics found for this type of discharge, an increase of current with a small increase in voltage must result in both an increased positive ion production at the anode as well as an increase in electron collection from the plasma. The ions are necessary to maintain the plasma between the anode and negative glow with the increased electron current and perhaps even play an additional important role in the electron production at the cathode corresponding to the current increase. Ordinarily the anode glow supplies sufficient positive ions for this purpose. When the anode is made small and the cathode large, resulting in a large current density at the anode, the normal anode glow cannot produce the necessary ions, and the anode spots develop to provide these ions. The results of the Langmuir probe analysis show that the space potential in the vicinity of the anode spot reaches a value close to the normal anode fall at a comparatively large distance from the anode. As a result, the electrons acquire sufficient energy to ionize while their remaining path to the anode is yet long enough to permit a high probability of ionization. The anode fall region should be related to the production of positive ions in a manner somewhat analogous to the way in which the cathode fall is related to the release of electrons from the cathode under positive ion bombardment. In addition to producing positive ions, the spots effectively increase the anode area and provide an efficient means of collecting electrons from the plasma.

The mechanism involved in the case of the disk anode may be explained as follows. When the current density at the anode is small, a thin glow surrounds the anode. This glow in turn is surrounded by a plasma where the net space charge is very low but which contains of the order of 10^8 particles of each sign per cm^3. The equipotentials surrounding the anode probably differ only slightly from the electrostatic case. The drop through this glow is about the same as the first ionization potential of the gas. Although the distance traveled by the electrons which acquire this energy is small, they produce sufficient positive ions for the requirements of the discharge. As soon as the current reaches such a value that this normal glow cannot supply sufficient positive ions, this glow or sheath thickens, with the drop through it remaining about the same. The increase in current to the disk anode is not uniform. As is shown in Fig. 11, the lines of force converge toward the edge providing a lens or focusing

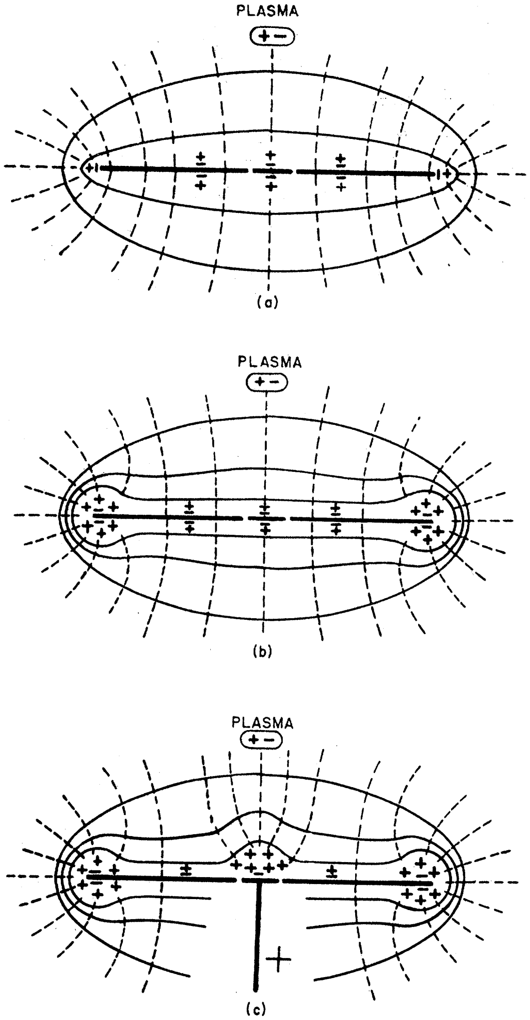

FIG. 11. Possible charge, field and potential distribution about the disk anode. (a) When the current is small. The auxiliary anode is at the same potential as the anode proper. A thin electron sheath surrounded by a positive ion sheath exists near the anode. In the outer regions a plasma exists when the net space charge is nearly zero. (b) The same except that the current is large. (The field converges electrons towards the edge producing intense ionization.) The increased positive space charge near the edge attracts still more electrons to this region. (c) The same as (b) except that the auxiliary anode is maintained positive with respect to the anode proper. Under these conditions a spot forms on this auxiliary anode for the same reason as at the edge.

effect which concentrates the electrons on the edge where they produce a corresponding intense ionization. The presence of these groups of positive ions with their low mobility results in a net positive space charge in this vicinity which in turn tends to further concentrate electrons upon this region. The space potential within the spot may rise above the anode due to this space charge, as occurs in the low voltage arc. The net result is the formation of the spot at the edge. The lower diagram in Fig. 11 shows how this same mechanism operates in the case of the artificially grown spot on the auxiliary anode. Here the distortion of the equipotential resulting in the "lens effect" is produced at will by raising the potential of the auxiliary anode above the anode proper. A spot, once produced, should be stable and persist as a spontaneously formed spot. This was observed experimentally. In the case of the spherical electrode, the same process occurs except that some mechanism must operate to initiate the spots. Any localized thickening of the sheath due to surface irregularities or other causes will serve this purpose.

Electrons must converge toward these spots and from them positive ions must diverge into the plasma. These beams have magnetic fields associated with them which together with the intrinsic positive charge possessed by each spot produces the even spacing around the edge of the disk and the regularity over the sphere. Such a beam of positive ions collects electrons from all around it and tends to converge them to the boundary of the spot, furthering the process detailed above.

Such a mechanism does not require a greatly enhanced drop across the discharge as a whole to produce a large increase in current. The change in space charge distribution merely results in an extended positive ion beam which in turn collects more electrons from the plasma.

The maximum in the individual spot characteristics is evidently responsible for the formation of many spots rather than the continued growth of one spot. The reason for this maximum is not immediately apparent. Possibly below and near the peak the electrons have sufficient energy to excite and not ionize except by cumulative action. Beyond the peak, ionization may occur directly resulting in a dimming of the spot and less electrons reaching the probe since the slower electrons produce a thicker electron space charge sheath near the anode. A spectroscopic examination should reveal the energy changes occurring on collision within the spot. It must be remembered that although the current to the auxiliary anode decreases, the current as a whole increases as another spot is forming elsewhere. At high pressures, because of frequent collisions, the spot can extract electrons from a relatively small region of the plasma resulting in many spots close together while at low pressure this region from which electrons are drawn is large and the spot correspondingly large.

Anode spots will play an important role in those devices in which the currents are large and the anode areas small. They should occur at the anode when the transition from glow to arc is approached and in gaseous discharge devices employing thermionic emitters or cathode spot emitters where the discharge current may become large.

SEPTEMBER 1, 1940 PHYSICAL REVIEW VOLUME 58

A Complete Isometric Consistency Chart for the Natural Constants *e*, *m* and *h*

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(Received December 12, 1939)

The purpose of this paper is to show in greater detail the construction and use of a certain type of consistency chart already briefly described by the author in a previous paper, and by means of it to exhibit, with a few minor changes and some important new additional data, the present status of the dilemma regarding the values of *e*, *m* and *h* which grows out of the discrepancy between various results of careful measurements of functions of these variables. The discrepancy itself remains practically as glaring and just as unexplained as ever. Scales have been added permitting the values of *e*, *m* and *h* corresponding to any intersection point to be read off directly.

THREE-DIMENSIONAL REPRESENTATION

VERY few experiments have been performed which measure any one of the three atomic constants alone without involving one or both of the others. Thus the values of *e*, *m* and *h* are usually obtained by combining the results of several types of experiment and solving a system of simultaneous equations. There are, however, a great number of ways in which this can be done and these lead to different results so that it becomes desirable to find some graphic representation to exhibit as impartially as possible the inconsistency situation.

In a recent article[1] on the natural constants which will here be referred to as I NC the question of the interconsistency of measurements of functions of the atomic constants *e*, *m* and *h* was discussed by means of a graphic chart which was essentially an isometric[2] projection of a three-dimensional plot of the situation. If one thinks of the values of *e*, *m* and *h* as plotted along the three axes of a three-dimensional rectangular Cartesian coordinate system, then each function of *e*, *m* and *h* for which some physical experiment yields a numerical value is represented by a surface in this three-dimensional space. Since the functions of *e*, *m* and *h* determined by experiment are essentially product functions the general equation for such a surface is

$$e^p h^q m^r = A_i \quad (1)$$

in which certain of the exponents may, of course, be zero; e.g. the case of the direct determination of *e* independent of *h* and *m* ($q=0$, $r=0$). At least three of these surfaces are required to determine a point (e, m, h) in this three-dimensional space. With more than three surfaces over-determination may exist and this may be coupled with inconsistency so that various dif-

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[1] J. W. M. DuMond, Phys. Rev. **56**, 153 (1939).

[2] Since several different methods of plotting the interconsistency of determinations of functions of *e*, *m* and *h* have been proposed and R. T. Birge (Phys. Rev. **57**, 250A (1940)) has recently even discussed "an indefinitely large number of variations of such types of chart" it seems advisable to adopt suitable descriptive names for some of the outstandingly interesting ones. The present author wishes to take such a responsibility only in the case of the type of chart which he originated and he suggests for it the name isometric chart.

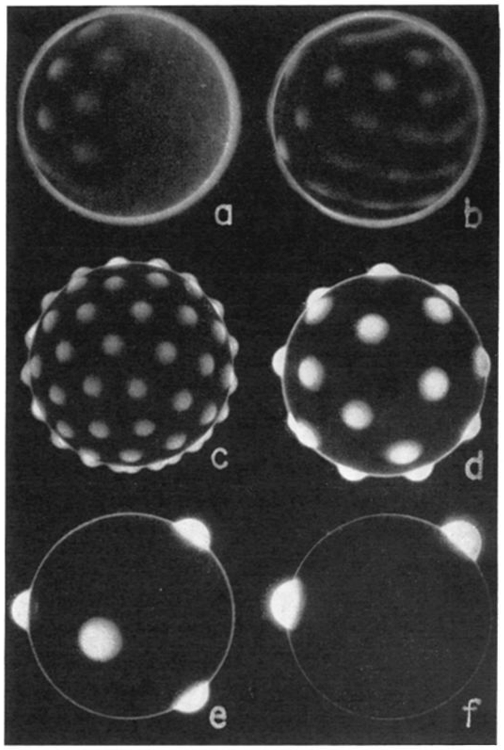

FIG. 1. Anode spots on a spherical anode. (a) Pressure 1.25 mm Hg, current 420 ma; (b) 1.20 mm Hg, 420 ma; (c) 0.79 mm Hg, 425 ma; (d) 0.41 mm Hg, 465 ma; (e) 0.36 mm Hg, 390 ma; (f) 0.26 mm Hg, 400 ma.