

THE AUDION.—II.*

A NEW RECEIVER FOR WIRELESS TELEGRAPHY.

BY LEE DE FOREST.

Concluded from Supplement No. 1665, page 350.

I HAVE laid considerable stress upon the potential gradient or "variation" layers which exist near the surface of the electrodes when the external applied electromotive force is considerable, for the reason that their existence serves to play a very important rôle in the response of the audion to minute high-frequency oscillations.

If the velocity of negative ions is very large compared to that of the positive ions, the curve representing the distribution of electrical intensity between the two electrodes is represented by the following, which is typical.

When ions of both signs are present in the gas and when the electric field is so strong that most of the positive ions are driven from the anode and the negative ions from the cathode (the filament), we will have an excess of cations in front of the anode and of anions surrounding the cathode.

It is seen that the variation in potential lies chiefly in the thin layers of gas in front of the two electrodes. It is convenient to speak of these regions as the "variation" layers. As Thomson points out, in passing from the inside to the outside of the layer of ionized gas we have to pass across a layer of electricity. This will produce a discontinuity in the electrical intensity equal to 4π times the surface density of the electrification.

There may thus be a great difference between the electric intensity inside the layer and that just outside. The potential drop across the layer is proportional to the square of the current; the falls of potential at the positive and negative electrodes are proportional to the squares of velocities of the positive and negative ions; and the velocity of the ions is proportional to the electric force acting upon them.

These variation layers at the electrodes of the audion make still more striking its similarity with the cathode-ray tube. In the cathode tube a sudden drop in potential called the "anode fall of potential" occurs quite close to the anode; and in the layer called the Crookes dark space, or cathode dark space, there is a still greater fall in negative potential. But the voltages here are enormously higher than those in the audion. As the gas pressure in the cathode tube diminishes, the dark layer, or the cathode drop layer, becomes broader. $D = \alpha + \beta \lambda$; that is, the width of the dark space is proportional to the mean free path of the molecules, beyond a certain distance α in front of the cathode. Schuster found that the thickness of the cathode drop layer increased slightly with the current passing through the gas; but Wehnelt found just the reverse. Both may be correct on different sides of some particular value of the current for which the width of this space is a minimum. This is interesting in view of the fact that there is a certain current flux across the gas of the audion for which the response of the Hertzian oscillations is maximum; supposing this response is maximum when the width of the variation layer around the filament is minimum.

Within the cathode layer there exist only negative ions, these being shot off from the cathode. Right outside of this, in the region called the "cathode glow," ionization of the gas from collisions with these negative ions begins, and the width of the cathode dark space is about the range of the "mean free path" of the ions.

If a similar state of affairs exists around the filament of the audion, and if this mean free path of the cations coincides with the excursion of the corpuscles during one half the oscillation period of the impressed Hertzian vibration, we might expect under these conditions a maximum effect of response to oscillation of the particular wave-frequency. Or a similar effect might be expected if the excursion in question is that of an ion from the cathode across the gas up to the layer surrounding the anode.

The extent to which the sensitiveness of the audion is governed by a very slight change in the heating current, or in the potential drop across it, seems to lend plausibility to such an explanation. And it has been shown that in conducting flames at atmospheric pressure, a negative ion acting under a potential gradient of 10 volts per millimeter would travel approximately 1 millimeter, or a commonly found distance between the electrodes in the audion, in $1/1,030,000$ part of a second, which time-interval is of the order of one-half of the wave period of some of

the longer oscillations used in wireless telegraphy. For reduced gas pressures the natural excursion of the ion would be more rapidly accomplished, but its velocity can be governed within wide limits by regulating the applied electromotive force. When we send more current through the filament we increase the potential difference between filament and anode as well as increase the heat. Both changes act to increase the ionic velocity.

In Humstedt's experiments where a cathode-ray tube was exposed to high-frequency oscillations, the width of the cathode drop layer, or dark space, diminished as the frequency of the oscillations increased; as if there might be some connection between the period and the time involved in the immigration across. And many facts observed in connection with the audion otherwise difficult to explain tempt one to suppose that here the degree of response is connected with the relation between the product of velocity of the ions by the distance between the electrodes and the period or half-period of the electrical oscillations received.

When the anode consists of two parallel plates instead of a cylinder there will be a maximum of positive electric density along their vertical edges. The more intense parts of the electric field will involve the larger number of ions, and on the anode these will generally be located at the vertical edges of the parallel plates, provided these are not too far from the filament.

With this type of anode a peculiar and sudden inflection point in the current-flux diagram, as the heating current is gradually increased or decreased, is noticed. The flux goes on increasing, then suddenly drops back to a lesser value; at the same time a click is heard in the telephone in the *B* circuit. Then as the heating current is still further increased the *B* flux is again increased. These same cusp points in the curve are obtained if the *A* circuit be kept constant and the *B* voltage is increased instead.

Similarly, a click is heard when the flux current is being reduced from a higher value, only the location of the cusp on the curve of decreasing current is not coincident with but lags behind that observed when *B* is being increased. This second cusp point shows a sudden increase in the flux current, when the critical point is reached, to a value previously passed through. Naturally the sharpness of these cusp points can be smoothed out or quite obliterated by putting impedance in the *B* circuit in series with the telephone.

The diagram (Fig. 9) shows the relative magnitude of these sudden alterations in the flux current obtained with a certain sample audion, and also the decided hysteresis effect, showing how the actual *B* current lags behind the increasing or decreasing electric field which produces it. This hysteresis effect is very like that obtained when the molecular structure of iron is altered under a changing magnetic field. Doubtless it is here due to a reluctance of the ions to accommodate their paths and velocities to the impelling electric forces; and the area included between the two curves represents the work lost in accomplishing this conformation.

These hysteresis curves are always obtained even though the anode is in the form of a cylinder or flattened cylinder without the vertical edges; but the reactive cusp points in the curves are never obtained save with two plane anodes connected together.

Zeleny* has found a similar very curious hysteresis effect in the currents obtained from the ions from a platinum wire when heated and exposed to ultra-violet light. When the metal was cooling these currents were greater than those for the same temperature when the metal was being heated. In this case heating the wire produces some change in its surface, possibly in the amount of gas condensed thereon or absorbed by it, from which it recovers very slowly.

As *B* voltage is increasing and *A* current is increased and decreased, I find that the points at which the cusps occur on the increase and decrease *A-B* curves coincide more and more nearly, and at the same time these cusps become less and less violent. The hysteresis effect is less pronounced as the *B* voltage is increased. As shown in the curves for a large *B* flux the two *A-B* curves for increasing and decreasing *A* current coincide almost exactly until *B* flux is reduced to a certain amount. They may again cross each other at a lower point of *B* flux, again diverge, and then coincide once more near their origin. These curves were all taken with audions of the double-wing type, which feature may account for some of the very peculiar characteristics observed.

The filament is always at some part nearer to one wing than the other. Hence the *B* flux is chiefly concentrated on this wing or portion of wing, like a beam of cathode rays. We may suppose that as the *B* voltage is increased, as when more heating current is passed through the filament, the flux is increased and spreads out over this wing until a new sheaf or "ray" of ions, starting off from the filament from another part or in a new direction, suddenly leaves that wing and takes by preference a shorter path to the opposite wing. We would suppose that a new path thus taken would first be located on one of the vertical edges of the wings parallel to the filament.

This sudden diminishing of the intensity or density of the original beam of ions may be accompanied by a decrease in the velocity of propagation of the ions, and thus the resultant flux be actually less than before. The reverse operation will occur when the *B* flux is being decreased from a high value.

When the anode consists of one wing only, no such reverse cusp-points, or reversals of the flux increment, have been obtained. With a single-plane anode, however, there is found a point at which the flux if increasing assumes a sudden increase in magnitude, representing an abrupt rise in the otherwise smooth flux-voltage curve; and the reverse when the current flux is being decreased.

These effects seem to relate to the increased values of the positive variation layers along the vertical edges of the anode which parallel the filament. The distribution of the charge upon the surface of the plate may be described as analogous to that of a thin film of liquid which coalesces and is heaped up along the edges, and from which, when the liquid is by any means drawn away, there is a sudden recession; the liquid, on account of the surface tension, letting go or taking hold of the edge all at once.

It is significant that just at a cusp point the sensitiveness of the audion to the hertzian oscillations attains a marked maximum. Under the critical conditions then obtaining the slightest change in the applied electromotive force is accompanied by relatively great changes in the *B* flux.

In framing any theory of the action of electric oscillations in the audion a variety of complex, contradictory phenomena are met with, exceedingly puzzling to explain. An example is the fact that a continuous-current instrument either in the *A* or the *B* circuit shows absolutely no change of deflection either of increase or decrease, when *B* is large and the audion in its most sensitive condition. If only the positive halves of the oscillations pass from anode to filament these should increase the reading of a milliammeter in the *B* circuit during the passage of a long series of wave-trains of sufficient intensity. Or else the negative halves of these oscillations might be expected to diminish to a greater degree the positive charge on the anode, and result in a diminution of the *B* circuit. Or if both of these acted equally and oppositely no signal would be obtained at all, for the telephone diaphragm is utterly incapable of following such rapid increase and decrease in the *B* current, even if its impedance would allow these pulsations to pass through the circuit. Neither would the ear detect such vibrations.

If on the other hand the integrated effect of a complete hertzian wave-train were either to increase or decrease the *B* flux, a long succession of such effects, all of which must be of the same sign, ought to cause a change in the needle's deflection, as when a long Morse dash is sent out from the transmitting station. We have no reason to suppose that one wave-train, the result of one spark, would produce a momentary decrease in the *B* flux, indicated by a click in the telephone, and that the next succeeding wave-train from the next spark would cause an opposite increase in the *B* flux, and another similar click in the telephone. Such action would of course explain why a loud sound in the telephone might not be accompanied by any change in the sluggish ammeter reading, similar to the case with the magnetic detector.

The following explanation of the phenomena which seems to account for many of the peculiarities of this paradox has been suggested. It should be remembered that if the negative half of the electric oscillation can not pass through the gas from cold anode to the filament the audion electrodes during that half-period will act merely as the two armatures of a condenser. Even when close together, their mutual capacity, when the gas is cold, is exceedingly small, and only a very small positive charge can be held bound on the filament; or if there are sufficient free positive ions in the hot gap the complementary posi-

* For its name, Audion, a title as beautiful as it is appropriate, I am indebted to my assistant, Mr. C. D. Babcock, who has been of utmost service to me in the development of this device almost from its inception.

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* Zeleny, Physical Review, vol. xii., 1901.

tive charge will be held just on the outside of the "variation layer" at the anode.

The fall of potential across the variation layers at anode and cathode are proportional to the squares of the velocities of the positive and negative ions; and the ionic velocities are proportional to the electric forces acting upon them. Supposing then that during the positive half of the electric oscillations the velocity of the positive ions is increased at the anode layer, and during the other half period the velocity of the negative ions is increased, due to the changes in the electric force acting upon them. Then regardless of the sign of the change of the velocities the potential drop across the variation layers (which varies with the square of these changes) will be increased during the entire passage of the oscillation train.

The layer will act during this interval like a condenser, the potential drop across which is momentarily increased, which momentary increase will disappear with the passage of the wave-train. It will be as though the plates of a charged air condenser were suddenly further separated and then brought suddenly back to their normal positions; or as though the specific inductive capacity of the dielectric were decreased and then increased. This operation being repeated for every spark at the transmitter a listener in the telephone in the *B* circuit will hear a sound whose pitch is exactly that of the spark, while an ammeter in that circuit will show no variation in its deflection.

As the fall of potential across the variation layers is proportional to the square of the current passing and to that of the impelling electric force, it is readily understood how, by regulating the heating current and the *B* voltage, an optimum value of the electrode drop may be obtained for which the effect from any given received impulses will be a maximum. Also how by varying the distance between the electrodes the sensitiveness of response may be regulated.

Thomson states that the current between two plates for a given difference of potential varies inversely as the cube of the distance between the plates, up to the saturation-current stage. But in the case of the audion, where the cathode is an incandescent filament, the law seems to be quite different. Thus for two anodes of equal area, one approximately four times as far from the filament as the other, the two currents were as 21 to 8. The flux here varies more nearly as the inverse distance.

The potential difference required to produce saturation is proportional to the square of the distance between plates and to the square root of the intensity of ionization. This latter depends on the temperature of the filament.

In the case of the parallel plates, only one of which is incandescent, or if both are heated but below yellow heat so that only ions of one sign (positive) are present and carrying the current, then this current as Thomson shows is:

$$i = \frac{9 R V^2}{32 \pi d^3}$$

where *R* is the velocity of the ion under unit electric force, *V* the potential difference, *D* the distance between the two plates. According to this formula the current varies inversely as the cube of this distance. But this formula will hold only when *R* is independent of *X*, which it will not be when the temperature through the space is not uniform. It holds also only for currents that are small compared with their saturation values, for the saturation currents depend not upon the velocity of the ions but upon the number of ions produced in unit time at the surface of the hot electrode.

But in the case of the audion with small potentials, the closer the electrodes are together the more rapidly will the *B* current increase as the potential drop is increased. The trajectories of the ion are shorter and they therefore undergo fewer collisions, reunions, and retardations when the electrodes are close together.

In an audion where the anode is far from the filament the saturation current is not attained with the *B* voltages used with the audion in wireless telegraphy. We sometimes have instead its inverse counterpart, a saturation voltage, so to speak. As shown in the curve, at potentials from 10 to 18 volts a slight potential increment is accompanied by a very large increase in flux. And within these limits the sensitiveness of electric oscillations may be a maximum. The cusp points when present are generally found near these points of inflection in the flux-voltage curves.

In some cases a remarkable lag or "creeping effect" is observed at this saturation stage. As shown in the curve, the milliammeter needle crept slowly up after *B* was raised to 14 cells, from 18 to 26 divisions. The current flux required something like 15 seconds in this instance to attain its full value. The filament in this case may have been undergoing some change which caused it slowly to discharge more and more corpuscles until that stage was reached where the recombination of oppositely charged ions in the gas exactly equaled the output of negatively charged

ones from the incandescent surface. Sometimes this creeping is accompanied by a loud frying sound in the telephone.

MAGNETIC EFFECTS.

Thomson shows that at low gas pressures and high ionic velocities the ions, when placed in a strong magnetic field, will travel along the lines of strong mag-

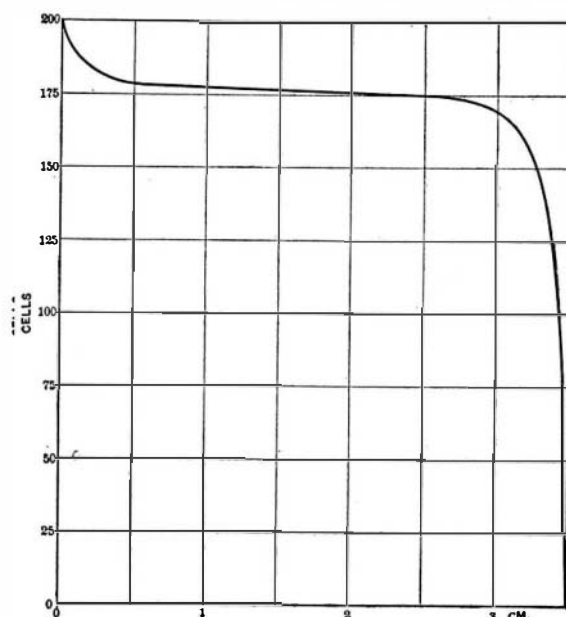


FIG. 7.

netic force; but when the product of velocity and field is small the ion moves parallel to the electric force. If both magnetic and electric forces are uniform, the ions both positive and negative will move in the same direction and perpendicular to both *E* and *H*. When the electric field is not uniform but radiates from a point, and the magnetic field is uniform, the ion will describe a spiral traced on a cone of revolution whose axis is parallel to the magnetic field.

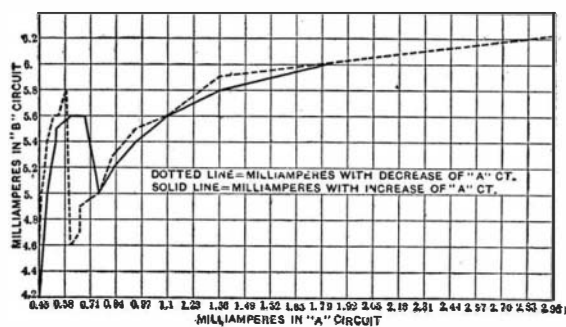


FIG. 8.

If the directions of *E* and *H* coincide, the path of the ion itself is a helix of gradually increasing pitch, with its axis parallel to the lines of magnetic force. The radii of the spirals will be small compared to the length of the mean free path of the ions. This is especially true for the negative ions, even when the motion of the positive ions is but little affected by the magnetic field.

If the electric field is not uniform (and it is not in

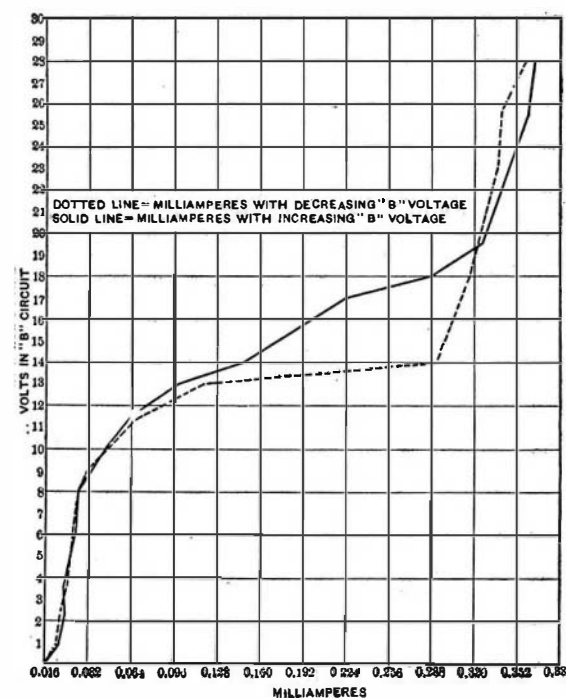


FIG. 9.

the audion where the negative charge is located on the small cylinder of the filament instead of on a plane surface) the paths of the ions will not be cycloids, but in any case the ions will be turned back by the magnetic field after traveling a certain distance *d*, from their source. Thus they will never get farther than *d* from their source.

When the lines of magnetic force are perpendicular to the discharge in the cathode-ray tube, the magnetic field at all pressures retards the discharge and diminishes to a considerable degree the great drop in the electric force which occurs in the negative glow.

In general it can be assumed that in a strong magnetic field the ions tend to follow the lines of magnetic force. The smaller the velocity of projection the more nearly does the path of the ion coincide with a line of magnetic force. In cathode-ray tubes the boundary of the negative flow may coincide with the lines of magnetic force.

In the case of the audion if the lines of a strong magnetic field pass through the gas parallel to the plane of the anodes, a marked reduction in the flux is obtained, sometimes amounting to 20 per cent. This effect is greater when the south pole of the magnet is nearest that leg of the filament which is attached to the negative terminal of battery *A*. The negative charge on this leg is of course greater than on the other, for the negative charge on the other is the resultant of the negative potential of battery *B* and the positive potential of battery *A*. And when the lines of magnetic force are so directed as to tend to sweep some of the negative ions off from the parts of the anode nearest to the filament leg which carries the greater negative potential, the reduction of the flux across the gas will be the greatest possible. Hence the magnetic polarity observed.

If the filament extend above the top of the anode, say for 0.5 centimeter, then a magnetic field parallel to the filament legs may tend to force certain lost ions into a downward trajectory so that they will strike upon the anode instead of passing off above it. In this case only is an increase in the *B* flux observed as a magnet is brought up to the audion.

In general the flux will be diminished by the magnetic field. When the magnetic lines pass perpendicular to the plane of the wings the negative ions which are traveling in the direction of the magnetic force, from filament to wing, will be accelerated, but those originally traveling out from the filament in the opposite direction will be bent around or deflected from their direct paths; so the resultant will be a decrease of the total current flux.

When the field is intense, a marked frying or hissing sound in the telephone is heard, especially with the two-wing anode, and when the magnetic force is parallel to their plane and thus affecting mostly the ions which are streaming toward their vertical edges. In the hissing arc parts of the arc are in rapid motion in the unstable portion around the edges of the positive terminal. Possibly also the presence of oxygen in the gas enters into the phenomena here as it does in those of the hissing arc. As the magnetic field lengthens the arc so here it lengthens the paths of the ionic discharge.

The hissing is much more violent when the surfaces of the anode instead of being plane are punched full of little holes whose ragged and protruding edges offer a greatly increased opportunity for the ions to travel irregularly under the combined forces of the magnetism and of the electric charges heaped up at all such points and edges. In this particular audion, I could get a great range of singing or squeaking sounds as the heating current was varied. Where the velocity of the ions is a maximum their deflection by the magnetic field will be lessened.

If the *B* flux is too great to give maximum sensitiveness of response, bringing up a magnet to the audion will increase the strength of the wireless signals, because of the reduction of the *B* flux. Or if this flux be already below the optimum then the presence of the magnet may decrease the sensitiveness. This effect may be more pronounced for one wave-frequency than another, in which case the audion can be attuned by regulating the magnetic field to which it is subjected.

Consider the case where the electric oscillations instead of being introduced into the audion through its interior anode are brought up to a metal plate outside a vessel. Electric displacement currents instead of conduction currents must then act upon the ions within the vessel and on the charges upon the electrodes.

Now in the case of an electromagnetic wave, where *H* and *E* are perpendicular to each other and to the direction of propagation, Thomson shows that if the product of *H* × *e* is large (*e* being the electric charge on a carrier) the average velocity of the ion parallel to the direction of *E* is zero, and the wave will carry the ion along with it. When, however, *H* × *e* is small (no external magnetic field) the effect of the Hertzian wave will be to superimpose on the undisturbed motion of the ion a small vibratory motion parallel to the electric force of the wave and thus perpendicular to its direction of propagation.

A very convenient form of audion for investigating the relations which the distance, area, etc., of the electrodes bear to its response is had by using a pool of mercury for the anode. This is conveniently held in one or more pockets blown in the walls of the glass

vessel, and the filament so placed as to pass closer to some than to others.

Quite frequently I obtain with this arrangement two maxima of sensitiveness to the same transmitter, the filament heating current remaining unchanged; thus one maximum for $B=12$ volts and a second for $B=18$ volts. Again the sensitiveness is maximum when the mercury surface is as near as possible to the filament. When a globule has rolled out of its pocket, exposing a new surface for the anode, sometimes half a second elapsed before the sensitiveness is again restored. This form of mercury tube was especially sensitive to the influence of a magnetic field.

The optimum or critical voltage of B becomes less after this audion has been heated a little time, as though the heated mercury vapor began to act to increase the conductivity of the gas. This critical voltage keeps reducing as the vaporization proceeds, and with a sudden jar on the tube I can bring this down, one cell of B at a time, accompanied by a loud click in the telephone at each reduction. Sometimes a similar reduction of the B flux amounting to as much as 25 per cent can be obtained with the double platinum wing type of audion, by striking it smartly; or a sudden increase in the flux may be obtained.

The heating current when a large anode surface is used is less than that required to produce the same degree of sensitiveness with a small pool of mercury as anode. In general the flux is quite proportional to the area of the anode, other conditions remaining unchanged. A mercury arc also may be substituted for the filament, but such an arrangement is apt to be noisy in the telephone.

When the hertzian oscillations are passed through the filament instead of through the gas, they require

to be of great intensity to give any response whatever. Any results from the added heating effect which they may contribute to the filament are quite insignificant. The response when the audions are connected up in parallel, or series, is always less than for one alone.

In a tube whose two-plane anodes are fitted on hinges and backed with small iron disks so that their distances from the filament can be regulated by an external magnet, I find the response to a long wave-length greatest when this distance is the greatest possible; while to a wave-length of about one-half this, the response is decidedly better when the wings are nearer to the filament. Of course the B flux is greater in this latter case, other conditions being unchanged; but the selective quality in this tube just described seems to be due to the regulations of the distance between anode and cathode rather than to other factors.

The manner in which the audion should be located in the oscillating circuit, as well as many other considerations, show conclusively that it is a "potential-operated" rather than a "current-operated" relay receiver. At the same time its advantageous sluggishness of action, as explained above, renders it additive in its response to the energy of an entire wave-train or even of a series of wave-trains. Hence its excellent and marked selective qualities.

A large number of experiments have been carried out with a view to reducing the filament heat necessary to give the inclosed type of the audion the extreme sensitiveness which now characterizes it. This is now attained at normal brilliancy of the filament, or a little below; never at excessive heats. Thus the life of an audion should be that of an incandescent lamp of the same class of filament and voltage.

Filaments have been coated with alkali metals or

salts, or vapors of these introduced into the tubes. Experiments along these lines and with various dissociable gases are being pushed with gratifying promise of our soon being able to achieve the present marked sensitiveness even at red heats; or of still further multiplying the sensitiveness.

Radio-active compounds, applied for example between juxtaposed metal disks and heated, give little encouragement. At the low voltages used no increase of conductivity by their means has been observed, although Swinton has found that a radium coated cathode in a cathode-ray tube has a marked action in facilitating a luminous cathodic discharge, when the cathode is heated to redness. The mere presence of radium in the tube is insufficient to produce the effect.

Spontaneous ionization, that is the ionization independent of the electric field, as for example that produced by the X-rays, does not increase the current flux. Only the ions produced by the electric field itself close to the cathode, and by the heat of the cathode, are effective.

It is required that the audion be made with scrupulous care; a trace of impurity in the gas may produce surprisingly large effects in the potential drop across the variation layer. The presence of a mere trace of moisture may cause great difference in the behavior of a tube.

In all this work a bewildering host of new and puzzling phenomena is continually encountered. By its nature clean and pretty, fascinating in its ever new phases, gratifying in the efficiency with which it responds to the difficult demands of a new and intricate art, the audion combines infinitely delicate matter and forces, at once offering rich fields for study to the physicist and delight to the practical man.

ELEMENTS OF ELECTRICAL ENGINEERING.—VI. INCANDESCENT LAMPS.

BY A. E. WATSON, E.E., PH.D., ASSISTANT PROFESSOR OF PHYSICS IN BROWN UNIVERSITY.

Continued from Supplement No. 1664, page 326.

WHEN resistance is offered to the passage of a current of electricity, heat is produced. The case is analogous to that of mechanical friction, which is always a source of heat. In the transmission of energy, the evolution of heat, being a direct waste, is to be minimized, therefore suitably large conductors of good material are selected; then at the place where heat is wanted, the device which utilizes it is made of high resistance material of small mass. In the electrical case copper and carbon represent, in a remarkable degree, these two extremes, the metal having about 3,000 times the conductivity of the other. Since the amount of heat produced in a conductor varies directly as the resistance, a given current will heat a rod of carbon 3,000 times as much as one of copper. This proportion is so large that the copper rod may be considerably extenuated and allow the carbon to be some miles distant from the source of current, and yet allow the heat energy to be transmitted with only a few per cent loss.

Early forms of incandescent lamps were made with platinum wire loops in globes to which free access of air was permitted. Oxidizing, therefore, was inevitable, with consequent short life of the wire; but further, platinum is not a sufficiently refractory metal, and the point of incandescence is too near that of fusion; therefore, a slight excess of current readily melts the wire. By Joule's law, the degree of heating is known to vary as the square of the current, so a small increase in strength of current quickly reaches the danger point. Further, platinum has a resistance only about sixteen times that of copper—altogether too low a proportion to admit practical distribution of current to a large number of lamps at a distance from the dynamo.

The problem of the "subdivision of the electric light," as it was called, was really solved by Edison, in 1879. Already famous for his invention of the quadruplex telegraph system, and of the carbon-button telephone transmitter, the immediate effect of his new invention of the proper construction of an incandescent electric light was rather over-estimated; for immediately upon the announcement of the news in London, gas stocks took a violent decline.

The invention was really two-fold, for it consisted in making durable lamps of high resistance, and of connecting them in parallel, or multiple, with each other, rather than in series; this second part was really made possible by the attainment of the first. The multiple method of connecting limits the potential the dynamo is called upon to generate to that required for one lamp. Increase of number of lamps merely means more current; and, because each individual path is of high resistance, the total number of amperes does not exceed reasonable engineering abilities. By this method, now technically known as the "constant-potential" system of distribution, each

lamp, or other connected device, is rendered as independent of every other as are separate gas taps or water faucets.

Edison sought the ends of the earth to find the

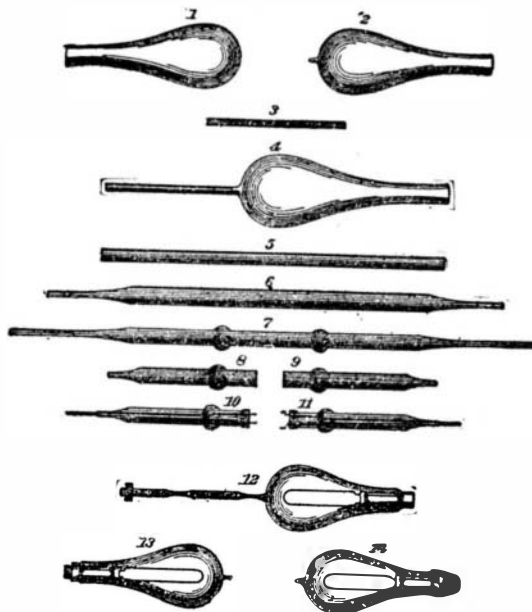


Fig. 24.—Details of Lamp Construction.

proper material for making the carbon threads or "filaments," as they are now called. He finally adopted shreds of bamboo. Other experimenters tried various other materials, bank-note paper, cotton, and silk threads receiving particular attention. Particularly has the extreme uniformity of the last made its use extremely enticing. Still the results with the bamboo were so good that its use was very general for more than a decade. But whatever the material of the filament, its incandescence in the open air would mean its almost instantaneous burning and disappearance. Edison inclosed the carbon in glass globes from which the air and other gases were highly exhausted, and led the current through wires sealed in the glass. He was not the first to use carbon filaments, but was the one who first made them of high resistance and adopted practical methods of manufacture. His fundamental patent, that was fiercely contested and openly infringed for years, involved the clear statements of the "combination of a high resistance carbon filament contained in a vacuum globe, and connected by wires sealed in the glass." The conflicting claims of other inventors were so interminable that the final decision of the courts in Edison's favor was not given until the patent had nearly expired. Others did make valuable inventions of processes, notably that by Sawyer and Man, and known as "flashing," to which the Edi-

son Company did not have the right; but it was a valuable asset of some of the competing companies.

The successive steps in the construction of incandescent lamps form a series replete with highly ingenious schemes and refined processes, attended with a delicacy of manipulation that is not exceeded in the making of a watch. Fifty distinct operations and forty inspections are needed to make a reliable lamp that, however, may sell for twenty cents. Though simple, even to plainness, it represents in some respects a device as near to absolute perfection as human hands and minds can produce.

Previous to about 1890, the use of the bamboo for filaments was very general, and though displaced since that time by the more uniform cellulose, the original process is sufficiently interesting to deserve mention. Selected sticks of the wood were cut in about six-inch lengths and split into as fine straws as ordinary knives would permit. They were then reduced to desired sizes by being drawn through successively smaller holes in hardened steel plates. Experience alone was the guide in determining just what lengths and diameters were needed to produce filaments of a desired resistance. Edison had arbitrarily decided that not less than 100 volts was needed for good dynamo operation, and with ten more volts thrown in, to be on the safe side, the present standard of 110 volts was established. The filaments were next bent over an iron block and packed in powdered charcoal in an iron or clay crucible and submitted to the intense heat of a furnace for ten to twelve hours. The volatile and easily combustible portions of the woody substance thereby disappeared, leaving, as it were, only the skeletons of the former structure—carbon threads. They were black and fragile, shrunk to about two-thirds of their former size. The fact that they were not completely destroyed is attested by the experiment of burning a newspaper in an open fire. If the draft is not too strong, the flame will leave behind a carbonaceous film of the merest gossamer thickness, yet on those delicate ashes can be seen the still denser carbon of the printer's ink.

With Edison, the next step was to attach the filaments to wires and seal them in globes, but the licensees under the Sawyer-Man patent submitted them to the "flashing" process. By this now universal process the individual threads are temporarily held in electrical contacts in an attenuated vapor of gasoline. Momentary passages of the current, whereby light is emitted in flashes, are allowed; the heat is sufficient to decompose the gas in the neighborhood of the filaments and solid carbon is deposited; naturally those parts that are the smallest will heat the most, deposit the most carbon, and thereby bring the whole filament to uniform size. This deposited carbon is denser than the original; in fact, it is pure graphite, and offers a smooth surface with metallic luster, so much so as readily to give the impression that the filaments are