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Contribution of Thomas A. Edison to Thermionics*

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A brief summary is given of the steps in the development of the thermionic vacuum tube. This leads back to the experiments of various people in the early 1880's, and particularly to the attempts by Thomas A. Edison to find the cause of the blackening of his newly developed incandescent lamps. Edison discovered during this work that substantial electric currents could flow between a hot carbon filament and another electrode across a high vacuum. Along with his contemporaries he wrongly ascribed the current to the flow of molecular ions rather than electrons. He, nevertheless, invented and built devices making use of these currents, the first applications of thermionics. The work received wide publicity at the time. Extracts from Edison's notebooks and other sources serve as illustrations.

THE story of Edison's part in the early development of thermionics has been told in various ways, in books, as part of a longer history, and in more specific articles.[1,2]

Having seen anew the original notebook entries of Mr. Edison[3] on this subject, and having witnessed almost the whole line of development of thermionic devices from the early days, I felt that I might add yet another version of the story, with some not-so-well known additional incidents and with possibly new interpretations.

The history of thermionics is very closely interlinked with that of the thermionic vacuum tube, and I shall begin by a brief review of the latter. This will put in as a foreground the goal toward which the early workers headed, without realization of its magnificence. Among the more prominent researchers contemporary with Edison's work may be mentioned Hittorf[4] and Goldstein[5] who observed relatively large currents flowing in a gas discharge when the cathode was raised to high temperature. They assumed, in the absence of better knowledge, that the molecular gases dissociated on contact with the hot cathode into ions that were the carriers of the current. Beginning in 1882, a series of papers were published by Elster and Geitel on the electrical effects of glowing wires, in air and in partial vacuum. Their work, and the state of the art, is well summarized in their 1889 paper.[6] They believed that the small currents in their experi-

* The substance of an after dinner address given before the Gaseous Electronics Conference of the Division of Electron Physics, American Physical Society, October 23, 1958.

[1] W. C. White, Gen. Elec. Rev. **46**, 537 (1943).

[2] V. Adm. H. G. Bowen, "The Edison Effect," pamphlet (The Edison Foundation, 1951).

[3] I am greatly indebted to the staff of the Edison Laboratory National Monument for letting me see and use the original material, and particularly to N. R. Speiden who helped to point out and select various items used here.

[4] W. Hittorf, Wied. Ann. **21**, 90 (1884).

[5] E. Goldstein, Wied. Ann. **24**, 83 (1885).

[6] J. Elster and H. Geitel, Wied. Ann. **37**, 315 (1889).

ments were generated from the gas molecules by "separation into electrically polarized ions," as had been proposed by Schuster.[7] The story of Edison's work will be told in greater detail in the following, but first we return to more modern times.

I am told that there are now in use in this country between one and two billion thermionic tubes. I first saw vacuum tubes in 1913 when there were not so many. This was in the laboratory of Professor A. Hoyt Taylor, who later contributed the fundamentals of radar. He had acquired a pair of audions, invented by Lee de Forest in 1907. In a 2-in. glass bulb there were mounted a filament, wire grid, and plate or wing as it was then called. It was a terrific detector of radio signals compared to the usual crystal detector, but it was also pretty finnicky. The plate voltage had to be just right, and the filament temperature then at a critical value that gave a faint blue glow in the tube. Ideas as to how it worked were in a state of even fainter glow.

I next saw the vacuum tube in 1917, after doing some other things and then joining what is now the Bell Telephone Laboratories. I remember being shown a vacuum tube that had recently been developed, and which looked a good deal sturdier than the old audion. It was not only a good reliable detector, but I was amazed to hear that it could amplify signals, and could generate high-frequency current with power in watts. I think it was what was then called an L-tube, developed for telephone repeater service, and for aircraft communication. In back of this is an interesting story.

In 1912 the telephone people were working on the possibility of putting amplifiers on long telephone lines. They were working on two kinds of amplifiers. One was a repeater invented by H. E. Shreeve based on the gain obtained in the carbon button of the telephone transmitter when suitably coupled between an incoming and outgoing line. The other was a mercury arc device invented by a young fellow who had joined the group the previous year, H. D. Arnold. The Shreeve repeater and the Arnold arc were crash projects because a transcontinental telephone line was planned. Then in November of 1912 de Forest came to the Western Electric engineers one day and said that he had discovered that his audion would amplify signals. He had a little box with him to prove it. Would the telephone people be interested?

They were interested, and studied the contents of the little box. Dr. Arnold, who had recently studied electrons in Millikan's laboratory, decided that electrons were involved in the audion and that the operation would be improved if the blue glow could be gotten rid of. He reasoned that what was needed was the highest vacuum obtainable. A development project was set up, staffed by very competent physicists, chemists, and engineers. A new kind of vacuum pump was ordered from Germany, and pumping and processing techniques were developed. The electrode structure of the tube was improved mechanically. The metal filament was replaced by an oxide coated one, and the modern vacuum tube was born. The transcontinental line was set up for test in 1914, with all three repeaters in circuit. The vacuum tube won out handsomely, and it has had little competition since then, until quite recently.

In 1915 the first tests on transatlantic radio telephony were carried out by the same organization. Here the tubes were used not only as receivers, but as oscillators, amplifiers, and modulators. There were in the transmitter banks totaling 750 tubes, each of 50-watts output capacity. This was about two and one-half years after de Forest's historic visit.

At the almost identical time a similar development went on in the laboratory of the General Electric Company. The work there had its basis in the extensive work carried out on incandescent lamps under the leadership of Irving Langmuir, in this field the counterpart of Arnold. Here was evolved the very serviceable tungsten filament tube.

These were eventful years in experimental physics. They were the years when Laue discovered x-ray diffraction, when Knudsen did his work on the flow of gases at low pressure, when Gaede invented the mercury vapor diffusion pump out of which grew Langmuir's condensation pump and Buckley's aspirator pump, and when Buckley invented the ionization manometer. In these years Langmuir did his magnificent

[7] A. Schuster, Proc. Roy. Soc. (London) **37**, 317 (1884).

work on electron space charge, and evolved the first really clean surface, that of a well-processed tungsten filament. Langmuir's work at last settled the arguments over thermionic emission, as to whether it was some freak property of dirty metallic or other surfaces.

Let us now go back 15 years, to the turn of the century. Becquerel had just discovered radioactivity, Roentgen had discovered x rays, and Braun had invented the gadget that is now our television tube. Further, J. J. Thomson had just proved that the negative electrical carriers of cathode rays are much smaller than the negative ion of atomic dimensions in electrolysis and some gas discharges. This established the electron in the family of physics. Drude took up the idea, and in 1900 proposed that the electric current in metals is carried by these small new entities. Here Thomson took the ball again and suggested that perhaps these are the carriers that are emitted from hot metals, as in the Edison effect, owing to their high thermal energy. He asked his student O. W. Richardson to look into it. Richardson came through with his classic work on thermionic emission, in which by thermodynamic arguments he related the emitted current to the temperature and work function of the metal.

The Nobel prize winners who have worked on electrons make an imposing list: Braun, Thomson, Richardson, Millikan, Langmuir, Davisson, G. P. Thomson, and, perhaps, others.

This finishes the foreground of the picture. For the main subject, let us now step back another 20 years, to another lamp maker. The year was 1880. Thomas A. Edison was busy in his laboratory at Menlo Park developing his carbon filament incandescent lamp. The lamp was not on the market yet, but it looked very promising. The filament at that time was cut horseshoe shaped out of a certain kind of calling card, then carbonized and mounted on the lamp stem. This was sealed into a glass bulb that was then pumped with a Sprengel dropping mercury pump.

There was one trouble with the lamps, in that carbon from the filament would be transferred to the inside glass walls and this blackening reduced the efficiency and limited the life of the lamp. How did this blackening come about, how could it be prevented? On this they did a lot of speculating and testing. Then one day someone noticed that the positive end of the filament loop cast a light shadow on the glass, as if the carbon came from the negative end in straight lines and was intercepted by the positive end. Now, Crookes had shown the year before that cathode rays are negatively charged particles that proceed from the negative electrode toward the positive in a gas discharge. This suggested to Edison and his people that in their lamps negatively charged carbon atoms were projected from the filament, and only those from the negative end could get to the glass. A shadow would be left by the positive end. (There was no alternating current then, Edison was always a dc man.) The projection of carbon was called "electrical carrying," on the assumption that the carbon carried the current or, perhaps, vice versa. They ascribed it to the Crookes effect, still with some misgivings. It was to lead them on a long, wrong trail, yet with interesting experimental results.

Now, if the carbon particles are charged it should be possible to draw them to a separate electrode, away from the glass. Furthermore, it should be possible to measure the electric current to this electrode. On February 13, 1880, Edison entered in his notebook the first of a long series of experiments on prevention of carrying (Fig. 1). The drawing shows a lamp with the "horseshoe" filament, and an extra electrode inserted, a piece of platinum foil. The test was made by Charles Batchelor, one of Edison's engineers. The column of figures at the left in another handwriting refers, presumably, to a set of voltages or perhaps candle powers at which the tests were carried out. The results were evidently not conclusive because other tests followed.

A later entry that year, November 28 (Fig. 2), shows two added electrodes, differently disposed, for the "prevention of carrying." In July, 1882 (Fig. 3), the problem was still worked at. Here there was a considerable break in these tests, and this is understandable. On September 4, 1882 Edison opened his Pearl Street station in New York, the world's first generating station for supplying power to the new electric lamps. He had invented, designed, and built the generators, distribution lines, meters, switches, fuses, and

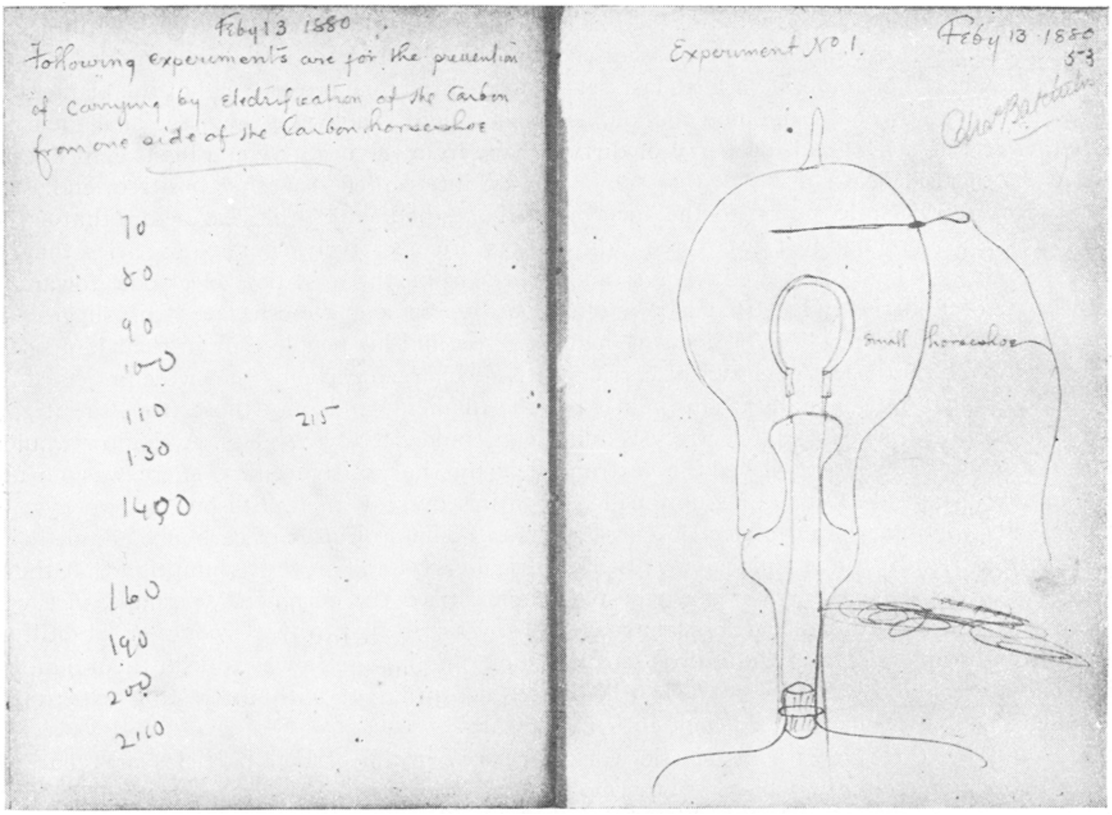


FIG. 1. February 13, 1880. Notation: "Following experiments are for the prevention of carrying by the electrification of carbon from one side of the carbon horseshoe." "Experiment No. 1."

practically all the things that go with electric distribution. He had been busy. Then again on March 9, 1883, there is an entry by Edison suggesting that magnetic fields might be effective (Fig. 4). The lamp was pumped by Martin Force (whose brother, Joe, also worked with Edison and who, years later, worked with me as a glass blower), and tested by John Ott. The results were evidently still discouraging so far as carrying was concerned, and other directives followed, suggesting various electrode materials, the effect of strong light, magnetic fields, etc. One note directed Acheson (later of graphite and carborundum fame) to "Try Everything."

An entry by John Ott on October 8, 1883 (Fig. 5), is interesting. Edison had asked him to set up a lamp with the extra electrode connected through a galvanometer to one side of the line. The purpose was to see if the current in this branch circuit could be used to show the voltage on the line. While this seems to be the first entry showing a galvanometer in the circuit, it is pretty certain that the current to the extra electrode had been measured before and found related to the temperature of the filament. This is the first application of thermionic current to a useful purpose. It is the first electronic circuit, with the first thermionic tube.

Edison saw a potential usefulness in such a scheme and, as was his custom, immediately applied for a patent on it, that was granted less than a year later. Figure 6 reproduces the patent drawing for a voltage regulator. There is a moving magnet galvanometer whose deflection would increase with increased voltage on the line and, therefore, increased temperature of the filament. Provision was made for both manual and automatic voltage control. We quote from the first page this clear statement:

"I have discovered that if a conducting substance is interposed anywhere in the vacuous

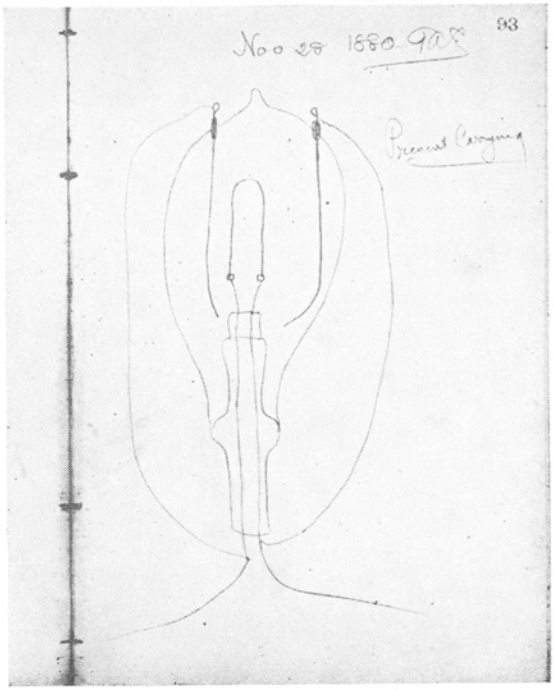


FIG. 2. November 28, 1880. An electrode to each of two filament terminals.

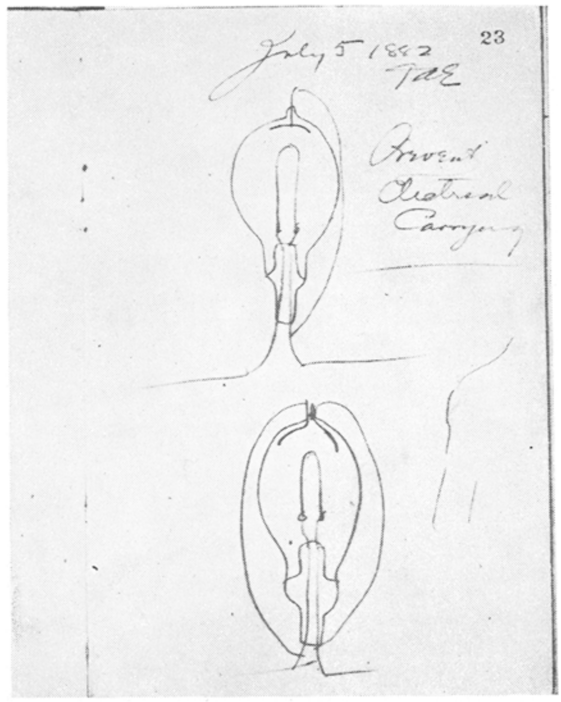


FIG. 3. July 5, 1882. Different electrode arrangements. "Prevent Electrical Carrying."

space within the globe of an incandescent electric lamp, and said conducting substance is connected outside of the lamp with one terminal, preferably the positive one, of the incandescent conductor, a portion of the current will, when the lamp is in operation, pass through the shunt-circuit thus formed, which shunt includes a portion of the vacuous space within the lamp. This current I have found to be proportional to the degree of incandescence of the conductor, or candle-power of the lamp.

"My invention consists in the utilization of this discovery for indicating or regulating variations in electromotive force, or for affecting electrical apparatus in any manner."

Edison, having thus informed the world of his discovery in a patent, proceeded also to do it in other ways. In the fall of 1884 there was an International Electrical Exposition in Philadelphia, held at the Franklin Institute and attended by many prominent people from different lands. Edison had a number of exhibits there, among them a model of his voltage regulator. The exhibits evidently had cards with them to explain their operation. The text prepared for the card on the voltage regulator is shown in part in Fig. 7. It is in the handwriting of Samuel Insull, the man who years later tried too hard to save his utility empire from ruin. The complete text reads as follows:

"APPARATUS FOR SHOWING THE CONDUCTIVITY OF CONTINUOUS CURRENTS THROUGH HIGH VACUUM

This is a recent discovery. The apparatus consists of an ordinary incandescent lamp in addition to which there passes through the glass a platinum wire which extends into the vacuum but has no connection whatever with the filament. To the end of this wire is soldered a copper extension wire the same as are connected to the filament so that connection may be made outside of the lamp. If this wire be connected to one binding post of a galvanometer and the other binding post be connected to the positive wire connected to the filament, no deflection will be obtained on an ordinary compass galvanometer until the lamp reaches the incandescence

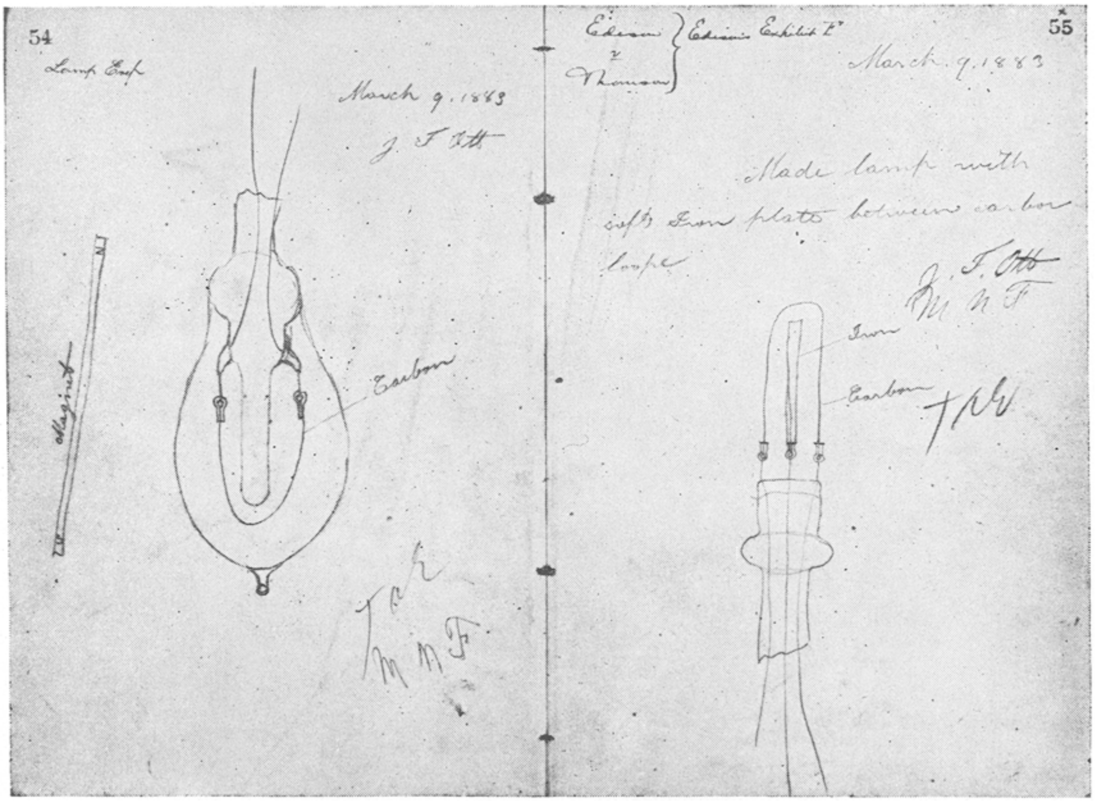


FIG. 4. March 9, 1883. Soft iron plate and external magnet.

of ten candles. At thirteen candles it gives a slight and continuous deflection and after this the deflection increases in a rapid ratio as the incandescence of the filament increases. At twenty-five candles a very powerful current passes through the galvanometer, it being perfectly continuous and capable of supplying a telegraph wire of 200 miles in length with current to work the instrument—notwithstanding that the globe is exhausted to a millionth of an atmosphere and the current must pass a space of at least half an inch."

In connection with the Exposition there was held a meeting of the American Institute of Electrical Engineers, October 7–8, 1884. Edison had a paper on his discovery prepared and presented at this meeting by Professor E. J. Houston. This was the Houston who later with Elihu Thompson organized the General Electric Company, and whose name still survives in the British Thompson-Houston Company. This paper was published beginning on page 1 of Volume 1 of the *Transactions of the American Institute of Electrical Engineers*. Figure 8 reproduces the first page of the text, "Notes on phenomena in incandescent lamps." In the text Professor Houston describes the experiment on current flow to a platinum plate in the lamp. The diagram shows the line or battery, the lamp with the filament and platinum plate, and the galvanometer connected to one or the other side of the line. He describes the experiments in detail, and is puzzled by them. Particularly, he wonders about the origin of the current that flows in the plate circuit. He says the vacuum is nearly complete, so he "cannot conceive of current as flowing across the vacuous space, as this is not in accordance with our preconceived ideas connected with high vacua . . . . I have no theory to propound as to the origin of these phenomena." Again: "It may be electricity flowing through empty space, which I don't think probable." He said it could be a Crookes effect, charged

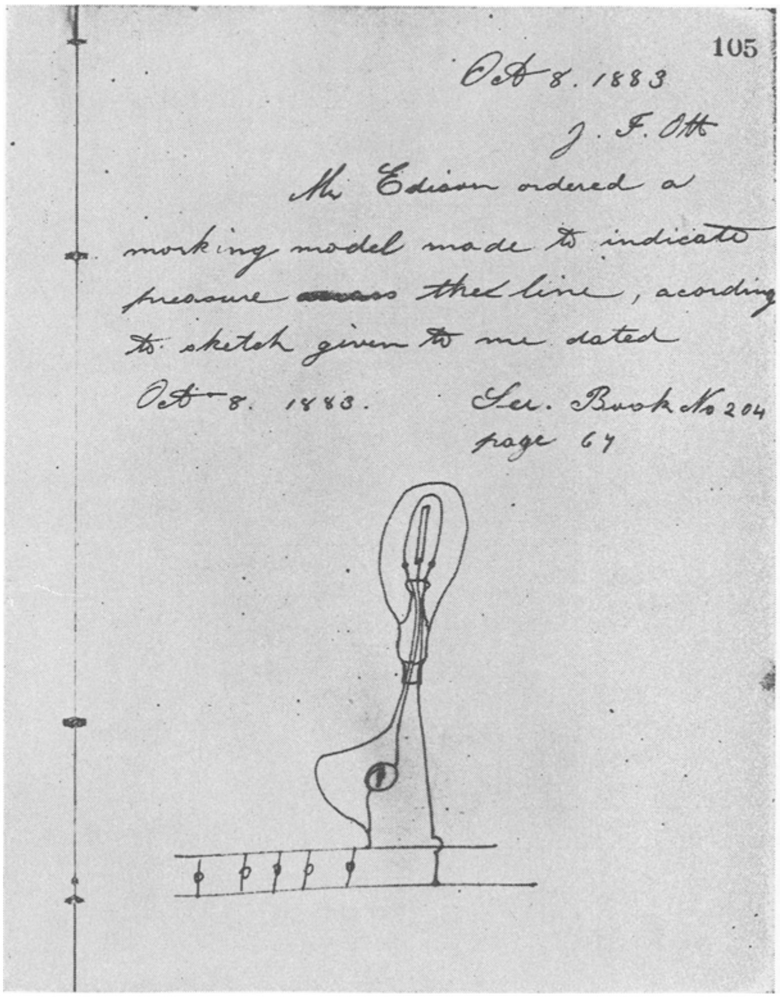

105
Oct 8. 1883
J. F. Ott
Mr Edison ordered a
working model made to indicate
pressure on the line, acording
to sketch given to me dated
Oct 8. 1883. See. Book No 204
page 67

FIG. 5. October 8, 1883. Voltage indicating circuit.

molecules flowing from plate to loop; but the direction of the current is wrong for this. "For my own part I am somewhat inclined to believe that we may possibly have here a new source of electrical excitement. That in some way the molecular bombardment against the platinum plate may produce an electrical current."

Among those present at the meeting was the eminent chief engineer of the British Post Office's telegraph service, Sir William H. Preece. In the discussion Preece said he had seen the exhibit and was puzzled by it. He thought there might be here a new source of electricity, but in his own mind he considered "the cause of this remarkable phenomena (sic) to be due to the Crookes effect. . . .

"Every other electrician present at the Exhibition, I think, has watched this experiment with great interest. I feel puzzled in reference to it, and I feel that it is one of those things that wants to be very carefully and cautiously examined. [How right he was!] I intend to exercise my persuasive eloquence upon Mr. Edison when I see him next week to induce him to give me one of those lamps, and when I go back to England I shall certainly make an illustration before our society there, and then make careful inquiry into it."

He did see Edison, who gave him several of his lamps with the added electrode. He published a paper the following spring, in the March, 1885 issue of the *Proceedings of the Royal Society*, entitled "On a peculiar behaviour of glow lamps when raised to high incandescence." In this paper

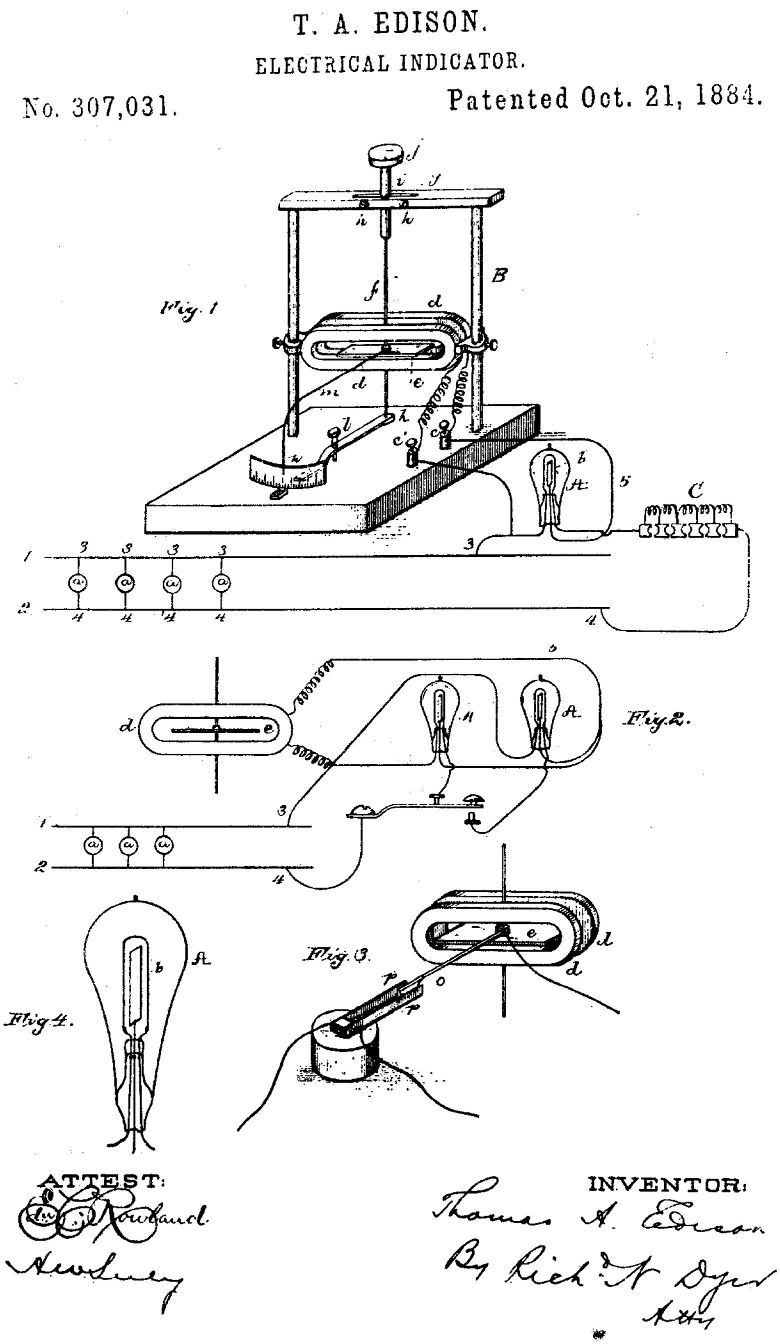
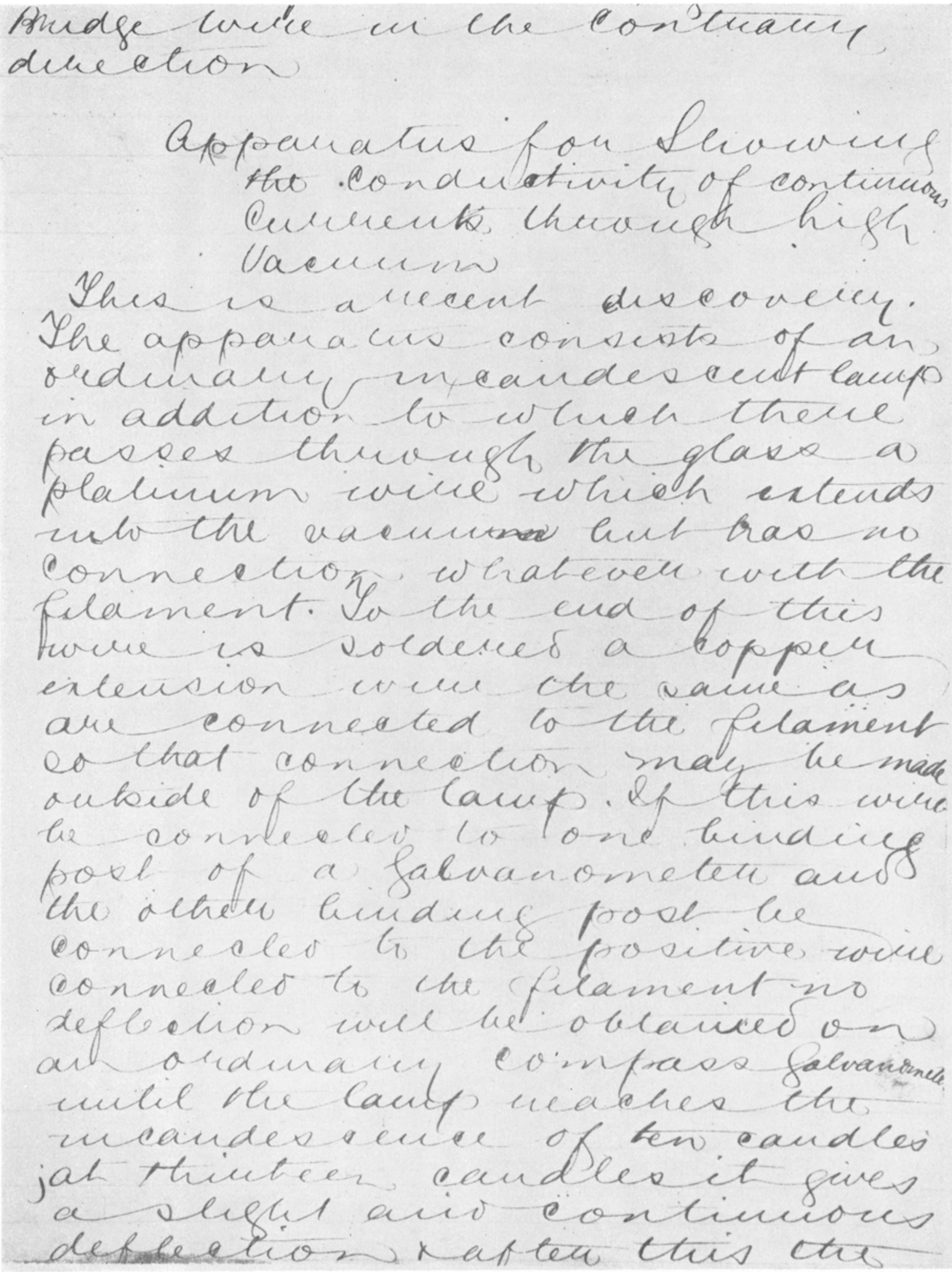


FIG. 6. October 21, 1884. Patent drawing for voltage regulating circuit.

Preece was the first to use the term "Edison effect." He measured current-voltage characteristics of the lamps, expressed in terms of "resistance of the rarefied space." Currents were as high as 7 ma, but he said the current flowed only when the filament was dangerously hot, so the device was not well suited for voltage regulation "as its ingenious discoverer originally proposed." Still misunderstanding what Crookes had observed, he assumed that the blackening was a consequence of the Crookes effect.

Next on the British scene was J. A. Fleming, then consultant to the Edison Electric Light Company, London. In late 1885 he published a paper in the *Philosophical Magazine*, "On molecular shadows in incandescent lamps." He had



Bridge wire in the contrary
direction

Apparatus for Showing
the Conductivity of continuous
Currents through high
Vacuum
This is a recent discovery.
The apparatus consists of an
ordinary incandescent lamp
in addition to which there
passes through the glass a
platinum wire which extends
into the vacuum but has no
connection whatever with the
filament. To the end of this
wire is soldered a copper
extension wire the same as
are connected to the filament
so that connection may be made
outside of the lamp. If this wire
be connected to one binding
post of a Galvanometer and
the other binding post be
connected to the positive wire
connected to the filament no
deflection will be obtained on
an ordinary compass Galvanometer
until the lamp reaches the
incandescence of ten candles
at thirteen candles it gives
a slight and continuous
deflection & after this the

FIG. 7. October 1884. Manuscript text of exhibit card, International Electrical Exposition.

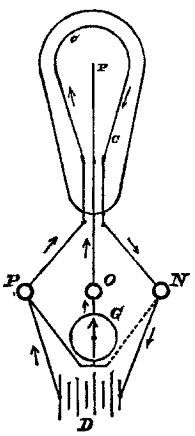
A paper read before the American Institute of Electrical Engineers, at Philadelphia, October, 1884.

NOTES ON PHENOMENA IN INCANDESCENT LAMPS.

BY PROF. EDWIN J. HOUSTON.

Prof. HOUSTON:—I have not prepared a paper, but merely wish to call your attention to a matter which, I suppose, you have all seen and puzzled over. Indeed, I wish to bring it before the society for the purpose of having you puzzle over it. I refer to the peculiar high vacuum phenomena observed by Mr. Edison in some of his incandescent lamps. I have in my hand an Edison incandescent lamp, having the same vacuum as the ordinary incandescent lamp. This one, however, has, in addition to the carbon filament, a platinum plate, or strip, that is thoroughly insulated from the filament, and supported in the manner seen between the two branches of the filament, as shown in Fig. 1.

FIG. 1.



An Edison carbon filament, *c*, *c*, is placed inside an inclosing glass case in the usual manner. A strip of platinum foil, P, is supported as shown inside the loop. The binding posts, P and N, are connected to the ends of the carbon loop, and O to one end

FIG. 8. E. J. Houston, Trans. Am. Inst. Elec. Eng. 1, 1 (1885).

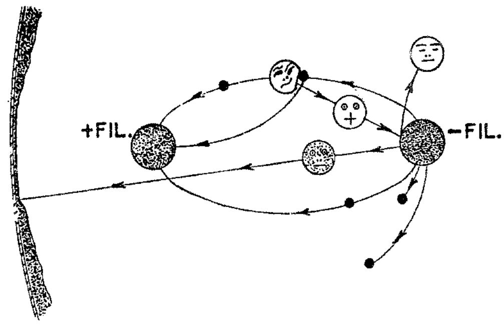
undoubtedly received Preece's message, but he claimed he had independently noticed the blackening and shadows in 1882, with about the same observations as Edison. He still had in mind these mysterious experiments, when in 1896 he published a 50-page paper in the *Philosophical Magazine* entitled, "A further examination of the Edison effect in glow lamps." In this paper he proved to his own satisfaction that a good vacuum is not a conductor, and that carriers are needed for the passage of current. The carriers he supposed to be the carbon particles, again the wrong interpretation of the Crookes effect. The trouble was that he was a little too early. The discovery of the electron was only two years away.

Crossing the Atlantic again, in 1897 an Edison engineer, J. W. Howell, read before the A.I.E.E. a paper on the "Conductivity of incandescent carbon filaments and the space surrounding them." This was work done at the Edison laboratory in collaboration with another Edison engineer, A. E. Kennelly. After discussing the filaments themselves he went on to the "Edison effect." They had used alternating current in the filament, and found then that both ends of the filament cast a white shadow. The current was still considered as carried by negatively charged molecules of carbon. Then they found that the current to the collecting electrode was the same when connected to either end of the filament. They had discovered rectification, and this fact was discussed by Kennelly and others.

This was about the state of the Edison effect just before the discovery of the electron. No more papers were published on the effect as it appeared in carbon filament lamps. On the inventive side, Fleming in 1904 applied for a patent on an oscillation valve for radio reception, better known as the Fleming valve. This was a rectifier tube. Later he disclaimed the application of it to low frequencies, possibly because of Howell's paper. A couple of years later de Forest applied for his audion patent, probably not starting from the Fleming valve but from another direction. And here we have come up to the foreground that we painted in earlier.

Now while we work our way back into the present, let us examine some questions that have undoubtedly occurred to you. First: What was the outcome of the Edison experiments on blackening? I have not seen an answer given directly but I think I know what it is. Putting added electrodes in the lamps did not solve the blackening problem. The solution probably lay in the gradually improved vacuum (getters were introduced around 1890), and in running the lamps at a low enough temperature so blackening was not serious. Carbon filament lamps, therefore, cast a dim and reddish light compared with modern lamps.

The second question is: What was it that happened in the Edison and other experiments on lamps, that so puzzled the experimenters? I have seen no attempt at an explanation, so again we are left to work out one for ourselves, and it will be quite different from what the early experimenters had the background even to surmise. We know that evaporation from hot bodies such as carbon takes place by the emission of neutral carbon atoms, not by charged particles. This means that the current was carried principally by electrons and not by negative ions. The vacuum they had was none too good, even if they called it a millionth of an atmosphere. The density of gas molecules was undoubtedly vastly greater than that of the evaporating carbon atoms. With a space current flowing, of some milliamperes at 100 volts or more, there would be considerable ionization of this gas, producing additional electrons, and ions with positive charge, not negative. The positive gas ions would bombard the negative end of the filament, and there give rise to emission of carbon atoms by the sputtering process. At this relatively low pressure both the evaporated and the sputtered atoms would go in straight lines from the filament to be deposited on the walls. But if sputtering exceeds evaporation at the negative end of the filament, then there would be a partial shadow cast by the positive end of the filament, just as if negative ions were emitted by the negative end. At the same time, in the flow of the electron current the negative end of the filament would be cooled by the emission of electrons, and the positive end would be heated by the electron bombardment. This would explain the difference in temperature sometimes observed between the two ends of the filament. The process is shown in a schematic way in Fig. 9, where dots represent electrons and circles are charged or neutral atoms. In particular, a neutral sputtered carbon atom is shown on its way from the negative end of the filament to the deposit on the glass wall, to which it will contribute unless it is intercepted by the positive end of the filament.



BLACKENING AND WHITE SHADOW

FIG. 9. October 1958. Illustration of the blackening process.

This explanation seems now fairly obvious and simple. But between it and the early observations there lies a series of experimental and theoretical works that were the major life work of many eminent scientists.

I have dwelt on the early areas of this history to show that Edison's discovery was an important part of it. The discovery of large currents flowing from a hot filament was not something that was recorded in a notebook and forgotten. Edison told people about it, he applied for a patent describing and making use of it, he caused it to be reported in the scientific literature, and it aroused a lively interest among eminent men of the day. The explanation of the phenomenon had to wait a couple of decades for the revolutionary ideas of Thompson, Drude, and Richardson. The truth then turned out to be that the carriers of negative charge were not carbon atoms in Edison's experiments or other gas molecules in the Crookes effect, but electrons in both. Edison's contribution was not to explain the phenomenon, but to create and keep alive a keen interest in the mysterious side effect that showed up in the blackening of lamps, the Edison effect.