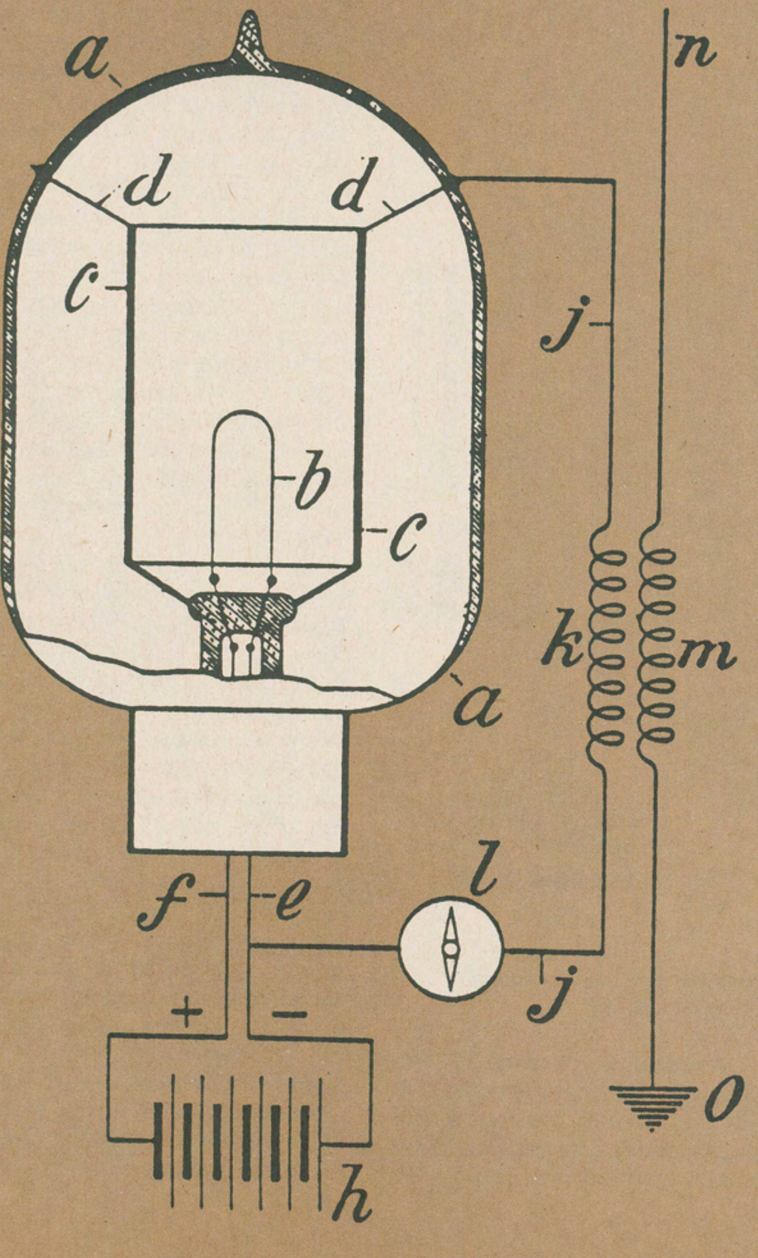
The Birth of the Vacuum Tube

BY JAMES P. RYBAK



Lee de Forest claimed he got the idea for his triode "audion" from watching a gas flame burn. John Ambrose Fleming thought that story was just so much hot air.

Wireless telegraphy held exciting promise at the beginning of the twentieth century. People with imagination could see the potential that the remarkable new technology offered for worldwide communication. However, no one could have predicted the impact that the soon-to-be-developed "oscillation valve" and "audion" wireless-telegraphy detectors would have on electronics technology.

Background. Shortly before 1900, Guglielmo Marconi had formed his own company to develop wireless-telegraphy technology. He demonstrated that wireless set-ups on ships could exchange messages with nearby stations on other ships or on land.

The Marconi Company had also transmitted messages across the English Channel. By the end of 1901, Marconi extended the range of his equipment to span the Atlantic Ocean.

It was obvious that telegraph lines with submarine cables and their inherent limitations would soon disappear. Ships at sea would no longer be isolated. No location on Earth would be too remote to send and receive messages. Clearly, the opportunity existed for enormous financial gain once reliable equipment was available.

To that end, tuned electrical circuits were developed to reduce the bandwidth of the signals produced by the spark transmitters. The resonant circuits were also used in a receiver to select one signal from among several transmissions.

Simple design principles for resonant antennas were also being explored and applied. However, the sensitivity and reliability of the devices used to *detect* the wireless signals were still hindering the development of commercial wireless-telegraph networks.

Inadequate Detectors. The detector most commonly used at the turn of the century was the coherer, developed by

Edouard Branly in 1890. Basically, the coherer consisted of a hollow, non-conducting tube filled with metallic filings. Normally, the coherer acted as an open circuit. However, when a voltage produced by a spark discharge was applied, the coherer became conductive and remained that way until the filings were shaken loose by tapping the tube.

The coherer was not a very sensitive or reliable detector and the tapping required between each telegraphic dot or dash meant that messages could not be transmitted very rapidly. Despite its limitations, the coherer was the best detector of wireless signals available at that time.

Marconi realized the need for an improved detector if his company was to attain its goal of establishing a worldwide wireless-telegraphy network. Already, he had modified the initial design of the coherer to increase its sensitivity and reliability as much as possible. Still, the coherer had too many fundamental limitations to ever become a satisfactory detector in commercial use, particularly on board a ship rolling in a stormy sea.

In 1902, Marconi developed and patented two types of magnetic detectors that overcame the need for mechanical tapping. They permitted messages to be sent at a more rapid rate than did the coherer. One design utilized a constantly rotating magnet, while the other employed a rapidly moving endless belt of iron wire.

Both magnetic-detector designs involved more mechanical complexity than was desirable and provided less sensitivity than was needed. The Marconi Company, however, did use magnetic detectors in its network of telegraph stations for many years until a better detector was available.

Which brings us to Lee de Forest. He also had dreams of establishing a commercially successful wireless-telegraphy company of his own. He, too, realized the need for a more sensitive and reliable detector and spent several years trying to develop a workable telegraph receiver, or responder, based on what was called the "anti-coherer-detector" principle.

Lee de Forest had gotten his idea for the detector from reading a report of a laboratory experiment that had taken place in Germany. The device initially consisted of a small piece of metal foil cemented to a glass plate. The foil was slit with a razor, a drop of water was

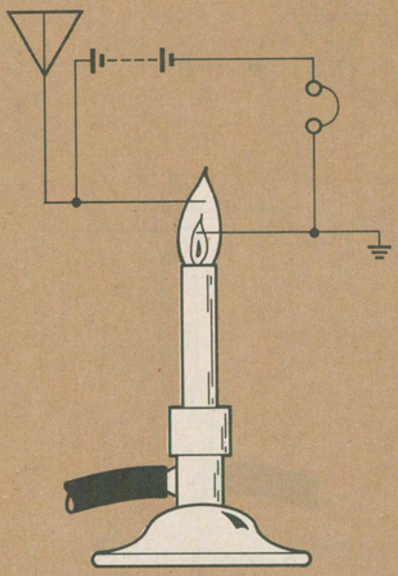


Fig. 1. Lee de Forest's first flame detector incorporated only one battery and needed no filament current.

placed across the slit, and electrical connections were made to the ends of the foil. The water drop acted as a short-circuit in the absence of a signal and as an open-circuit when a signal was present.

Tapping was not required between each telegraphic dot or dash, but the drop of water became electrically decomposed and unable to serve its function after a minute or two of use due to the minute electrical currents that flowed through it.

Lee de Forest refined the basic design and tried numerous substances as a replacement for the water drop. He never succeeded in producing a truly reliable anti-coherer detector for his telegraphic responder, or "sponder" as he called it.

However, Reginald Fessenden developed a sensitive fluid-based detector in 1902, which he called his "liquid barretter." Because it utilized a fine wire making shallow contact with a liquid (acid) surface, the barretter was not suited for shipboard use. Fessenden's patent on the barretter was also an obstacle to its commercial land use.

Both the Marconi Company and de Forest continued the search for a better detector. Their goals were the same and their searches led each to virtually identical thermionic devices by following what de Forest claimed were totally different approaches. The story of the development of the thermionic vacuum tube that follows clearly demonstrates how most significant advances do not occur overnight and usually involve the efforts of more than one person.

Edison Lights the Way. Thomas Alva Edison contributed substantially to the development of the thermionic diode through his work with the incandescent lamp. In 1879, he had produced a practical lamp with a carbon filament that operated on DC.

After each lamp had operated for a while, Edison noticed that a black deposit of carbon formed on the inside of the glass envelope. The carbon seemed to be coming from the negative side of the filament, since that was the side that always burned out. The deposits appeared everywhere on the inside of the envelope except where the positive end of the filament blocked the flow of carbon particles, leaving a clear line or "shadow" of the filament on the glass.

Since the carbon particles obviously came from the filament, Edison wondered if they might be electrically charged. He hoped that there might be a way of preventing the deposits from occurring and reducing the light output of the lamp.

Edison found that a current could be measured by a galvanometer connected between a wire electrode inside the bulb (but not touching the filament) and the positive end of the power supply. However, no current could be measured when the galvanometer was connected between the electrode and negative pole of the power supply.

This unidirectional current indicated that the current producing particles were negatively charged. Edison assumed the negatively charged particles were carbon particles. The flow of electrons that he was actually measuring would not be "discovered" until 1897 by J.J. Thomson.

Edison soon replaced the wire current-collecting electrode with a flat metal plate located between the legs of the filament. The plate proved to be an even more effective current collector.

Edison noted that the current flowing to the metal plate varied with the temperature (brightness) of the filament and, hence, with the applied DC voltage. He proposed using the modified incandescent lamp as a voltage-measuring device and obtained a patent on the design in 1883.

Unfortunately, being a confirmed believer in the use of DC voltages only, Edison never connected an AC voltage to the current-collecting electrode and never placed any greater significance on the unidirectional current flow he had observed. Hence, he never realized that his device could have been developed into the first thermionic rectifier diode. Nonetheless, Edison's device was later to have a significant influence on the development of the thermionic rectifier in England by John Ambrose Fleming.

William Preece, Chief Engineer for the British Post Office, came to America in 1884 to attend the International Electrical Exhibition in Philadelphia. While there, he saw some of Edison's inventions on display. Before returning home, Preece visited with Edison and obtained several of the incandescent lamps with the added metal-plate electrode.

Preece experimented with the modified lamps for a while. He was the first to use the term "Edison effect" to describe the thermionic emission from the filament that resulted in unidirectional current flow to the metal plate. Later, Preece apparently gave the lamps to the Edison Electric-Light Company of London.

Fleming Enters the Picture. John Ambrose Fleming would be knighted "Sir Ambrose" almost a half-century later by King George V for a lifetime of scientific achievement. In 1884, however, Fleming was a consultant to the Edison Electric-Light Company of London.

Fleming had noted the same darkening of incandescent lamps and the formation of a filament "shadow" observed by Edison. His initial experiments with the newly obtained modified incandescent lamps confirmed the other findings of Edison and Preece as well. However, Fleming made an additional and important contribution: he explicitly reported the unidirectional flow of current in an 1896 scientific paper.

He also observed that current flowed when the filament was heated by an AC voltage with a frequency between 80 and 122 cycles per second. With an AC filament voltage, it obviously didn't matter which side of the filament was connected through a galvanometer to the current-collecting electrode.

Fleming had thus come close to recognizing the potential use of this modified lamp as a rectifier of alternating current. However, at the time, he never suggested this or any other practical use for the device.

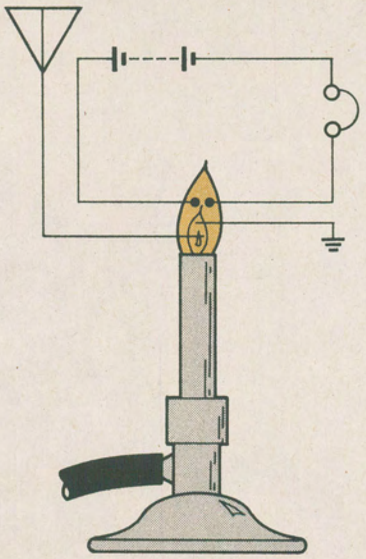


Fig. 2. The second style of flame detector had a local battery circuit which allowed it to operate better.

Fortunately for the future development of radio technology, Fleming was hired in 1899 as a scientific adviser by the Marconi Wireless Telegraph Company. He spent the first several years developing better transmitters and power-generating equipment for them. In 1904, Fleming was assigned the task of developing an improved detector. A suitably sensitive and rugged detector was still sorely needed by the Marconi Company.

Fleming soon decided to try one of the modified incandescent lamps as a detector, remembering its ability to produce unidirectional current flow from low-frequency AC. The question in Fleming's mind was whether or not the rectification effect would work at wireless-telegraphy frequencies.

An induction-coil based oscillator circuit was built to produce electromagnetic waves. A second resonant circuit was located some distance from it and was tuned to the oscillator's frequency. The second circuit included one of the modified incandescent lamps, together with a galvanometer to indicate the hoped-for rectified current.

When the oscillating circuit was activated, the needle on the galvanometer deflected, indicating rectification of the high-frequency wireless signals. Fleming had found, in that October of 1904, the wireless telegraph detector he was seeking.

He named his detector the "oscillation valve." It is important to remember that, being a diode, Fleming's device could only *rectify* oscillating currents; it could never produce them. More commonly today, we know his detector as the thermionic "valve" or "tube."

After this first wireless-detector experiment, the unheated current-collecting electrode in the lamp was replaced by a hollow metal cylinder surrounding, but not touching, the filament. Fleming immediately applied for patents on his oscillation valve in England, the United States, and Germany. The artwork at the beginning of this story is a reproduction of the drawing of the oscillation valve and detector circuit he included in his application for an American patent.

The British and American patents were granted to Fleming on September 21, 1905 and November 7, 1905, respectively. Those dates would become significant in later priority disputes.

A Flame Sparks de Forest. In September, 1900 de Forest was working in his room by gas light with his sponder one night and noticed something very strange. When he operated the key of the spark transmitter, the gas light flickered. He immediately called his assistant to observe this phenomenon and together they pondered its significance.

Their first reaction was to believe that the flickering flame represented a new type of detector action which might overcome many of the problems that plagued the sponder.

The two excited experimenters watched the flame respond to the keying of the transmitter and took detailed notes for several weeks. However, when the transmitter was moved to an adjacent room and the door was closed, the flickering of the flame stopped. It then became clear that the flame was responding to the sound waves generated by the spark transmitter and not to the electromagnetic waves.

Very disappointed, de Forest stopped the flame experiments. He later maintained, however, that the flickering flame started a train of thought in his mind that ultimately led to the development of the triode audion.

By 1903, de Forest had developed a flame detector that worked. He inserted two platinum wire electrodes into the flame of a Bunsen burner. He next connected a battery and a telephone receiver in series with the wires. One electrode was connected to an antenna and the other to a grounded water pipe. This arrangement as it was used, is shown in Fig. 1.

Signals from the antenna changed the conductivity of the flame which, in turn, changed the amount of battery current flowing. That produced an audible sound in the receiver's headset. The flame detector actually acted as a form of relay with the wireless signal triggering the flow of current from the battery. Lee de Forest's use of the word "relay" rather than "rectifier" would be crucial in his later legal battles.

With the flame detector, de Forest was able to copy transmissions from a ship in New York harbor. Two problems were immediately obvious, however. The ability of the flame to detect the signals was affected by air currents. Secondly, the two common electrodes used for both the antenna current and the battery current resulted in a by-pass path for the signal around the flame, resulting in decreased sensitivity.

The first problem was easily solved by shielding the flame against air currents. The second problem was solved by using one set of electrodes for the antenna and ground while a second set was used for the local battery circuit. That configuration is shown in Fig. 2.

The device's patent request was signed and witnessed on November 4, 1904 and filed on February 3, 1905. The 1904 signing date was twelve days before Fleming's patent application was filed. Those dates would become important when de Forest argued that the flame detector, and not Fleming's valve, inspired his later "audion."

Lee de Forest believed that the gases ionized by the flame produced the relay action. The flame, itself, was only the mechanism for producing the gas ionization needed. Other means of heating the gases sufficiently to produce ionization would result in the same detector action.

The best way to obtain a stable detector, de Forest reasoned, was to place the electrodes in a glass envelope and heat the gases to ionization with an external bunsen burner or by passing an electric current through carbon or tantalum filaments. Both heating techniques were tried. Lee de Forest quickly realized the advantages of filament heating.

The air inside the envelope was evacuated only to the point where the filament would not be oxidized when heated. A sodium or potassium salt was

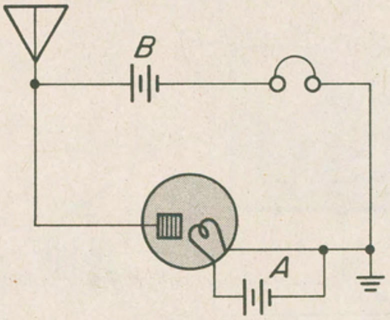


Fig. 3. Lee de Forest's diode audion detector allowed him to eliminate the flame by using a low-vacuum glass tube.

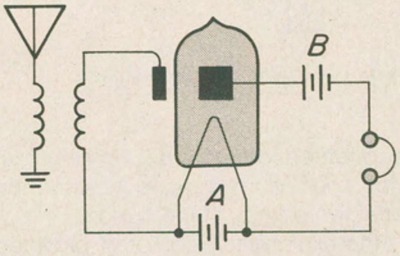


Fig. 4. The audion with external electrostatic control used a plate that was external to the the tube. It was soon followed by a device with an external coil.

placed inside the envelope to produce increased ionization.

Lee de Forest filed for several patents on this two-electrode "oscillation-responsive device" (as it was called in the patent applications) during the first half of 1906. More commonly, however, de Forest referred to the device as his "audion." The patents were awarded before the year's end.

Initially, the two electrodes in de Forest's audion were both filaments. Soon he eliminated the need for one battery by replacing one of the filaments with an unheated plate electrode. Lee de Forest now found that the polarity of the "B" battery in the circuit (shown in Fig. 3) appreciably affected the operation of the detector.

At this point it started to become clear that the Edison effect (thermionic emission) was involved in the operation of the audion. Prior to that time, de Forest had been convinced that the ionized gases in the tube were responsible for its behavior.

This single-filament detector, which de Forest also called an "audion," was superior to anything he had used previously. He received a patent on this device in the later part of 1906. The fact that this two-element audion was virtually identical to Fleming's patented valve was of no concern to de Forest. He later would argue that substantial differences existed between the two devices.

A Control Element is Added. Lee de Forest was convinced that his audion's sensitivity as a detector could be increased even more. Remembering the improvement the separate local circuit had made in his flame detector, he added an additional plate external to the glass envelope as shown in Fig. 4.

The external plate provided what de Forest called "electrostatic control" of the detector. He then built a similar device with a coil on the outside of the glass which produced "electromagnetic control."

The next audion de Forest built had two separate internal plates. The plates were located on opposite sides of the filament and the second plate was used as the control element. Lee de Forest was amazed with the performance of this audion. A patent application on this first triode audion was filed on October 25, 1906. Lee de Forest was granted the patent on January 15, 1907.

It did not take de Forest long to realize that the control element should exert an even greater effect if it were located between the filament and plate. Obviously, a solid control element would block the flow of current. A zigzag wire arrangement was used and was eventually developed into the "grid" found in today's tubes.

The three element "grid audion" proved to be a much better detector. The circuit in Fig. 5 is the one de Forest included with his January 29, 1907 grid-audion patent application. The patent was granted on February 18, 1908.

And that's how Lee de Forest's most famous and important audion was "born." It, like the earlier audions, was a low-pressure device. Therefore, calling it a "vacuum tube" is not correct.

It is important to realize, however, that the potential usefulness of the three-element (triode) audion was not immediately apparent. Few besides Lee de Forest initially were impressed with its operation as a detector.

The triode audion was expensive and its filament life was relatively short. The bulky and expensive batteries it required were another drawback. In contrast, the comparatively inexpensive crystal detectors, developed at approximately the same time, did not require batteries. The crystal detectors had added advantages in that they

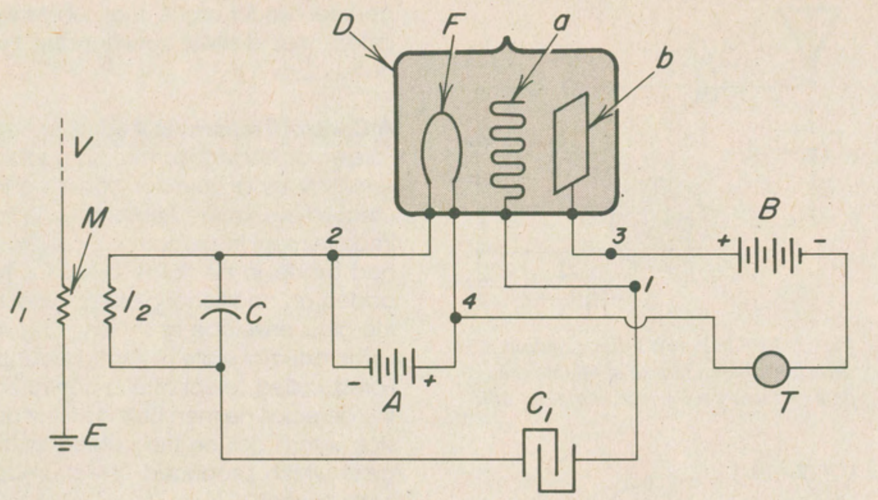


Fig. 5. Lee de Forest's grid audion was the first grid-containing low-vacuum tube. Multiple-electrode tubes were soon to follow.

were more reliable, simpler to operate, and virtually indestructible.

In his 1906 patent application, de Forest called the original triode audion a "device for amplifying feeble electric currents." The techniques necessary for using it as a true amplifier, however, would not be developed for almost six years.

Patent Problems. Other problems existed for de Forest, too. The Marconi Company of America owned the patent on Fleming's valve and maintained that de Forest's two-element (diode) audion infringed on that patent. Further, Lee de Forest's triode audion concept was based on his diode audion. Consequently, de Forest's right to manufacture and sell the triode audions was not without dispute.

Lee de Forest maintained that the idea for his diode audion came from his earlier flame audion, not from Fleming's valve. The records show, however, that de Forest knew about the Fleming valve and had some copies of it made for his own experiments late in 1905. In fact, one of de Forest's patent applications (for what he called a "static valve"), filed on December 9, 1905, refers to Fleming's valve by name. That patent application was filed several months before he applied for patents on his own diode audion.

A further claim by de Forest was that the use of a battery in the plate circuit of his diode audion distinguished it from Fleming's valve. He also argued that Fleming's valve was only a device for rectifying high-frequency wireless signals. Lee de Forest maintained that, unlike his own audion (which he still considered to be a relay), Fleming's device could do nothing to increase the effective energy of the signals.

The explanation de Forest provided concerning how his detector functioned differently from Fleming's was wrong. Both Fleming's and de Forest's devices were rectifiers, virtually identical in appearance and operation. The battery de Forest used in the plate circuit of his audion put a positive bias on the plate, but was not necessary for its operation as a rectifier. Lee de Forest's device was not, in any sense of the word, a relay.

While the legal position of the de Forest diode and triode audions was not very clear, that of the Fleming valve also was in question: Strictly speaking, Fleming did not "invent" the oscillation valve.

Books and Articles.

"Lee de Forest and the Triode Detector;" By Robert A. Chipman, *Scientific American*, March 1965, pp. 92–100.

Saga of the Vacuum Tube; By Gerald F.J. Tyne, Indianapolis, Howard W. Sams & Co., 1987.

70 Years of Radio Tubes and Valves; By John W. Stokes, Vestal, N.Y., The Vestal Press Ltd., 1982.

The Continuous Wave: Technology and American Radio; By Hugh G.J. Aitken, Princeton, N.J., Princeton University Press, 1985.

"The First Electron Tube"; By George Shiers, *Scientific American*, March 1969, pp. 104–112.

"The Life and Work of Lee de Forest"; (in 14 Parts), Edited by W.B. Arvin, *Radio News*, October 1924–November 1925.

He merely used the incandescent lamp Edison had modified and patented in 1883 for a new purpose—the detection of wireless signals. Edison's prior patent, together with some very broad claims in Fleming's patent application concerning the rectifying capabilities of the oscillation valve, made Fleming's legal position questionable.

As the markets for both Fleming's valve and de Forest's audion were initially relatively small, no resolution of the legal questions was pursued. The Lee de Forest Radio Telephone Company sold wireless equipment that incorporated grid-audion detectors to the U.S. Navy. It also sold the spherically shaped grid audions for commercial use. The Marconi Company used the Fleming valve, modified to include a grid similar to that in de Forest's triode audion, in its own network of wireless stations.

Amplifiers and Oscillators. In 1911, de Forest was hired by the Federal Telegraph Company. The company's goal of recording high-speed telegraph signals for later decoding created the need to increase the energy of the received signals. Lee de Forest now worked to get the triode audion to amplify at audio frequencies.

Lee de Forest and his co-workers achieved amplification in 1912 by using audio-frequency transformers to couple the signal to and from the audion. They also found it extremely beneficial to reduce even further the already low pressure inside the audion envelope. In time, the audion's spherical shape would become tubular and the generic name for this and similar devices, very appropriately, would become the "vacuum tube."

In the course of developing the amplifier, de Forest found that his circuit oscillated, a phenomenon commonly encountered by amplifier builders even today. The discovery that the triode also could be used as an amplifier or as an oscillator established it as a truly important electronic device.

Lawsuits and Stalemate. The Marconi Wireless Telegraph Company of America sued Lee de Forest and the Lee de Forest Radiotelephone and Telegraph Company in 1914 for infringement of its Fleming-valve patent. Lee de Forest and his company filed a countersuit for infringement of their triode-audion patents by the Marconi Company.

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VACUUM TUBES

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The Marconi Company admitted its guilt and was prohibited from further infringement. On September 20, 1916, a U.S. District Court ruled that de Forest and his company similarly had violated the Fleming patent. In short, neither the Lee de Forest Company nor the Marconi Company could manufacture triode audions without infringing on the other's patent.

This legal impasse was not resolved until after World War I. During the war, however, de Forest was granted legal immunity to manufacture grid audions for the United States Government.

Legacy of the Audion. Once the triode audion's capabilities for amplifying and oscillating were discovered, the development of regenerative and superheterodyne receivers quickly followed. Commercial radio broadcasting began shortly thereafter. In just a few years, the triode vacuum tube was joined by its more sophisticated tetrode and pentode relatives to make possible even more sophisticated electronic circuits. ■