THE VACUUM ELECTRONIC DEVICES: FROM THE ORIGIN OF ELECTRONICS TO CURRENT APPLICATIONS IN THE HIGH FREQUENCY FIELD

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ABSTRACT

Vacuum electronic devices were the basis of the first physical discoveries of the 19th century, starting from the low-pressure gas-filled tubes of H. Geissler in 1857 to the first vacuum tubes of W. Crookes in 1870. The Electronics started from the invention of vacuum diodes by J. A. Fleming in 1904 leading to the invention of pentodes by B. D. H. Tellegen in 1926. At the same time, gas filled tubes have founded the Power Electronics with the invention of ignitrons and thyratrons, while the classic vacuum tubes reached their latest evolution with the nuvistor series, which covered just over the Sixties of the last century. The klystrons and gyrotrons, the heirs of the microwave power vacuum tubes, are still today at the cutting edge of technology, and with these devices it is possible to reach in continuous operation powers of 1 MW at frequencies greater than 100 GHz. The article concludes with a brief overview of the state of research for new on-chip vacuum devices, which currently promise interesting applications in the high-frequency field.

KEYWORDS: *Vacuum electronic devices, vacuum tubes, gas-filled tubes, magnetron, klystron, gyrotron, on-chip vacuum devices.*

I. INTRODUCTION

Vacuum tubes, which in everyday modern life are an almost forgotten technology, in addition to having been fundamental to the development of electronics, are still extremely important in some advanced sectors of technology that are beyond common knowledge.
In this article we present a brief historical review of vacuum tubes, leading to klystron and gyrotron devices, the heirs of RF power vacuum tubes, which currently promise interesting applications in the high frequency field.
The presentation is organized as follows. In Section 2 we present a brief historical nores about the development of vacuum tubes. A description of low pressure gas valves for power applications and of microwave tubes is shown in Sections 3 and 4 respectively. The conclusions are presented in Section 5.

II. THE DEVELOPMENT OF VACUUM TUBES: BRIEF HISTORICAL NOTES

The predecessors of vacuum tubes were the low-pressure gas tubes developed in 1857 by Heinrich Geissler (1814-1879).

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Geissler was a physicist who, after his initial debut as a glass blower, later revealed himself to be a skilled builder of scientific devices and a very skilled experimenter: at the Rehinische Friedrich-Wilhems University of Bonn he was the first to study the light produced by the passage of electric currents in tubes with gas at low pressure.

These studies were the basis of the physics of gas spectroscopy. The device developed by Geissler consists of a tube equipped with two electrodes, an anode and a cathode, containing gas at 100 Pa, in which the electric discharge produces intense flashes of different colors depending on the quality of the gas: with neon a light is produced of a beautiful orange-yellow or bluish color if it contains mercury vapor.

These tubes are still used for illuminated shop signs or other advertising uses.

In 1861, using spectroscopy, William Crookes (1832-1919), a physicist and chemist at the Royal College of London, discovered thallium and subsequently, using the vacuum pump developed by the chemist Hermann Sprengel (1834-1906), managed to reduce the pressure of the gases contained in the tubes up to 10-3 Pa.

At this level of vacuum, a fluorescence could be observed on the glass of the tube which, in 1876, the German physicist Eugen Goldstein (1850-1930) explained to be caused by some type of cathode emission and which he called **Kathodestrahlen** (cathode rays). In 1879 Crookes demonstrated that these were negatively charged rays.

Several years later, in 1897, Joseph John Thomson (1856-1940), a physicist at the University of Cambridge, explained the phenomenon by showing that they were negatively charged particles with a charge/mass ratio much higher than that of any ion atomic, thus discovering **electrons**.

Meanwhile, before the discovery of electrons, it was observed that a hot cathode generated more intense currents, i.e. emitted more electrons, the so-called **thermionic emission**. Several researchers have studied this emission, including the French physicist Edmond Becquerel (1820-1891) and the British physicist Friederick Guthrie (1833-1886).

The first law that described the link between the thermionic current and the cathode temperature was that of the British physicist Owen Willians Richardson (1879-1959). This law was later improved by the German physicist Walter Hans Schottky (1886-1976).

The American inventor Thomas Edison (1847-1931) presented a patent in 1883 to use a vacuum tube as a voltage stabilizer, exploiting the strong dependence of the thermionic emission on the temperature of the cathode, but with little application.

It was the British physicist John Ambrose Fleming (1849-1945), while working for Guglielmo Marconi (1874-1937), who patented a vacuum tube in 1904, then called the **Fleming tube** (today **vacuum diode**), and applied it to the detection of radio waves. For this purpose, the asymmetry in the current characteristic with respect to the cathode-anode voltage was exploited.

Compared to the Crookes tube, this diode has a cathode with two terminals in order to allow it to be heated by the Joule effect. The progress achieved was in understanding the phenomenon and in having found a fundamental application for radio transmissions.

This idea actually founded **Vacuum Tube Electronics**.

It should be remembered, to be fair, that semiconductor diodes were already available, the first to use them in his experiments was the Bengali physicist Jagadish Chandra Bose (1858-1937). Called **cat's whisker diodes**, they consisted of a tungsten filament (**the cat's whisker**) in superficial mechanical contact with a galena crystal. Since this type of surface contact was not at all mechanically stable, the diode was particularly sensitive to shocks and vibrations and users were often forced to waste a lot of time trying to re-establish contact between the filament and the galena crystal. The vacuum tube eliminated these difficulties but presented the problem of the fragility of the glass, used as a casing to guarantee the vacuum, the limited life of the cathode, which was consumed following heating, and the production of heat. All these problems remained unsolved for almost the entire history of vacuum tubes until the introduction of metal tubes and modern cold cathodes.

The next step towards the vacuum diode was taken in 1906, simultaneously by the American physicist Lee De Forest (1873-1961) and the self-taught Austrian Robert von Lieben (1878-1913), with the introduction of the grid between the cathode and the anode thus obtaining the **triode**, the first vacuum tube capable of amplifying. The grid is a spiral metal element, positioned between the cathode and the anode, with a contact external to the vacuum tube and polarized so as to be able to control the passage of electrons.

The characteristics of these first vacuum tubes improved considerably thanks to the improvement of the techniques used to obtain an increasingly high vacuum and in particular to the invention, in 1915, of the diffusion pump applied to vacuum tubes by the American chemist-physicist Irving Langmuir (1881-1957).
A further source of improvement was the optimization of the geometry of the electrodes (anode, cathode and grid), developed following the understanding of the operating mechanisms of the triode, an understanding that was practically absent in the early stages. The valves soon came to have cylindrical symmetry.
Langmuir observed that the electrons emitted by the cathode tended to gather around it, creating a space charge which limited the emission of other electrons.
In 1913 he therefore patented a vacuum tube, called **tetrode**, with an additional grid compared to that of the triode, called space charge grid, placed between the cathode and the first grid, and positively polarized with respect to the cathode in order to favor the extraction of electrons from the cathode and obtain greater currents.
The German physicist Walter Schottky (1886-1976) in 1917 patented a vacuum tube, still a tetrode, with an additional grid compared to that of the triode called a screen grid. This new grid, placed between the first grid and the anode, had the purpose of isolating the anode circuit from that of the cathode and was connected to a circuit which at high frequencies presented a low impedance towards ground.
In this way the capacitance between cathode and anode was significantly reduced and consequently the problems of unwanted oscillations of the amplifiers were significantly reduced. Since the transconductance increased considerably, the number of tubes needed to obtain a given gain was also reduced.
Finally, the output impedance was generally much greater than that of the triode.
However, the tetrode presented a characteristic output function, i.e. anode current as a function of the anode-cathode voltage as the grid voltage varied, which was characterized, for low anode-cathode voltages, by a negative resistance section. This negative impedance could be used to produce oscillations, but almost always the main problem was the opposite, that of avoiding oscillations in the amplifiers.
To resolve the issues mentioned above, various variants of the tetrode were developed, such as the beam tetrode, until the development of the **pentode** in 1927 by the Dutch electrical engineer Bernard D. H. Tellegen (1900-1990). Both the space charge grid and the screen grid for isolating the input and output circuits appear in the pentode. The output characteristics had no negative impedance zones, and the output impedance and transconductance had higher values.
From that point on, vacuum tubes with a greater number of grids were introduced to take into account the needs of circuit designers to be able to have more terminals, from which to control the output current with multiple independent signals, so that a single valve could perform multiple functions simultaneously. Thus it was possible to reduce the number of vacuum tubes needed and therefore the size and cost of the circuits, especially the radios. The most complex valve was the **6-grid octode** introduced in 1939.
The latest evolutions of valves for receiving devices were the **nuvistors**, miniature valves measuring approximately 2 cm by 1 cm, introduced in 1959 as a last attempt to survive the arrival of transistors. Nuvistors were used to miniaturize tube radio and television equipment produced throughout the 1960s (they did not go beyond that period). They were made with a steel casing instead of glass, thus eliminating the problem of valve fragility, and used a ceramic base as an insulator for the feet. The small size allowed better performance in the high frequency field, from VHF to UHF, of particular interest for television broadcasts.
Apart from some internal mechanical simplifications, they did not present any innovations in the grill system.

III. LOW PRESSURE GAS VALVES FOR POWER APPLICATIONS

At the time of the invention of the vacuum diode, low pressure tubes were still being studied for low frequency applications for high voltages or high currents.

Peter Cooper Hewitt (1861-1921), American electrical engineer, developed the mercury vapor lamp starting from the Geissler tube, and from this experience in 1902 he obtained the mercury vapor discharge rectifier valve, the **ignitron**.

Instead of the metal cathode of vacuum diodes this valve used a well of liquid mercury. Also in this case the cathode was the source of the electrons while the anode was made of carbon in order to have a low thermionic emission; these choices therefore resulted in a straightening effect. The main difference with valves is that ignition requires striking an arc for a short duration in order to ionize the mercury vapor: the ions bombard the mercury well, keep it warm and favor the thermionic emission of the mercury . This valve was used for many years in high-power industrial applications to rectify used alternating currents.

With reference to Robert von Lieben's triode, already described in Section 2, we must add that his was not a high vacuum tube but contained mercury vapor, the presence of which influenced the characteristics of the device. For this reason we can see the von Lieben valve as the ancestor of the thyratron, a gas valve used as a switch for power applications, studied since 1914 by Irving Langmuir and then marketed at the end of the 1920s.

In these valves, the passage of current in the gas creates a plasma, i.e. an ionized gas, whose high electrical conductivity is fundamental for obtaining low voltage drops during the conduction phase. This plasma constitutes a space charge which is exactly what is prevented from forming in a vacuum tube. As a consequence, the thyratron does not have linear behavior but has an open/closed switch type conduction and is capable of managing currents higher than those of a vacuum tube of comparable size, with lower voltage drops thanks to plasma conduction. However, having solid metal cathodes and anodes, tyrathrons cannot handle high currents like those of mercury discharge valves where the cathode is a liquid metal, which obviously does not risk melting. The reduction of the voltage drop and the open/closed switch type behavior were the basis for the development of Power Electronics, which subsequently found great evolution with solid state electronic devices.

IV. THE DEVELOPMENT OF MICROWAVE TUBES

In the development of radio transmissions we started with long wave transmissions and then moved on to transmissions with increasingly higher frequencies. This led to the search for new tubes, currently still in use, better known as vacuum tubes, capable of amplifying at increasingly higher frequencies up to the GHz and starting to approach the THz. These new devices maintain some of the characteristics of the old valves, such as vacuum, cathode emission and the electric field to accelerate the electrons, but add other elements such as resonant cavities.

The transition from classical valves to these microwave tubes corresponds to the transition from lumped parameter circuits to distributed parameter circuits with resonant cavities. The majority of these vacuum tubes which allow to reach powers in the order of MW thanks to their high energy efficiency (up to 50%) [1-2] are still fundamental today in some specific applications as well as still in the development phase study and development. Among these in this article we examine the **magnetron**, the **klystron** and the **gyrotron**.

4.a Magnetron

Remembering that Thomson had already made use of the magnetic field on an electron beam to determine their charge-mass ratio, in 1921 the American physicist and engineer Albert Hull (1880-1966) patented a vacuum tube, **the magnetron**, made up of a diode placed in a magnetic field, with the idea of using the magnetic field instead of the electric field of the grid to control the current between the cathode and anode. Only in the following years, however, using multiple anodes, did several researchers understand that it was possible to produce oscillations at wavelengths of 10 cm (3 GHz).

As is known, electrons, in the presence of a magnetic field, are subject to the Lorentz force and follow circular trajectories in a plane orthogonal to the magnetic field. The frequency of the oscillations is determined only by the intensity of the magnetic field and the charge/mass ratio of the electron and is called the **cyclotron frequency**. The electrons, rotating, emit radiation at the cyclotron frequency, which is taken from the magnetron output.

The problem was to optimize the energy transfer of the electric field towards the electrons and from these the extraction of RF energy. So in the 1930s, multiple resonant cavity magnetrons were developed in various parts of the world [3-4], particularly in Germany, Holland, the USA and Japan. For this reason

they should be remembered among many: Hans Erich Hollmann (1899-1960), Klass Posthumus (1902-1990), Samuel Arthur (1901-1990) and Yoji Ito (1901-1955).
Finally, in 1940 the British physicists John Turon Randall (1905-1984) and Henry Boot (1917-1983) managed to produce microwaves with a wavelength of 10 cm (3 GHz), initially with powers of a few hundred Watts and later short with peak powers of 10 kW, peak with the aim of applying them to radars. At the end of the Second World War, magnetrons had managed to produce microwave oscillations of 10 cm with peak powers of 2 MW. Although the most popular application of the magnetron is in the microwave oven, magnetrons are still being developed today, particularly those with relativistic electrons (with high supply voltages), capable of peak powers of 3 GW for 10 ns pulses.

4.b Klystron

The **klystron** is a microwave amplifier, which does not use magnetic fields, and is capable of producing high powers using a beam of electrons which emitted from a cathode are accelerated towards an anode through a drift tube. Along the tube there are two resonant cavities into the first of which the microwave signal that needs to be amplified is injected.
The signal introduced into the first cavity creates a longitudinal modulation of the electron density, which develops fully along the drift space between the two cavities. The amplified microwave signal can then be extracted from the second cavity.
Given the presence of resonant cavities, the klystron is intrinsically a narrowband amplifier.
The theoretical principle underlying the klystron was invented in 1935 by the German physicist O. Heil (1908-1994) and the Russian physicist A. Arsenjewa-Heil (1901-1991).
In [5] they describe how to modulate the electron velocity of an electron beam to produce microwaves in a resonant cavity.
Given that the klystron is capable of achieving amplification gains of 60 dB, this device was the ideal complement to the magnetron in the creation of a radar: while the magnetron was in fact used in transmission as a source of high power pulses, the klystron was used in reception as a high gain amplifier.
Subsequently, the klystron was optimized to produce high powers and therefore had notable applications in radio transmissions; even today these devices are used on satellites for earth transmissions. Beyond that, they have been and still are used in accelerator physics as a source of RF energy to excite resonant cavities. Klystrons therefore remain unrivaled in the domain of high power at high frequencies, surpassed only by gyrotrons for frequencies above 10 GHz, while when moving to lower frequencies and powers solid state devices have taken over.

4.c Gyrotron

The **gyrotron** [1-2] is a microwave amplifier and generator between 10 GHz and 500 GHz, which uses a beam of electrons in a magnetic field [6-7]. Also in the gyrotron there is a beam of electrons emitted from a cathode which is accelerated towards an anode through a vacuum channel [8]. Coaxially to the channel, a magnetic field is produced by a superconducting magnet so that the electrons, as they drift, describe spirals on the plane orthogonal to the magnetic field. As with the magnetron, the electrons emit synchrotron radiation as they spin in spirals, but unlike the magnetron there are no radio frequency resonant cavities which, due to their size, would limit the power of the device due to wall losses. Unlike the klystron, where the microwaves create a longitudinal modulation of the density, in gyrotrons the modulation is in the transverse rotation mode. To maximize power, reducing beam instabilities, gyrotrons use ring-section beams, empty internally, produced by ring cathodes. Currently the gyrotron is the device capable of operating in the highest range of microwave powers and frequencies [2].
Thanks to the ability to continuously generate powers of a few MW at frequencies above 100 GHz with efficiencies even above 50%, the gyrotron is currently used to heat plasma in those laboratories that study plasmas in particular for nuclear fusion. In addition to this, the gyrotron is also an interesting device for use at lower powers because it is one of the few sources available in the field of millimeter waves capable of providing powers of 25 W up to 526 GHz and for this reason it is also used in NMR (Nuclear Magnetic Resonance) spectroscopy studies.

4.d Integrated vacuum devices

The possibility of using cathode emission also within integrated circuits has been studied for several years [9].

To the well-known advantages of integrated circuits, such as the reduction of costs and parasitic capacitances, one can add the advantages of the vacuum as a medium for the propagation of electrons, in particular the electrons in the vacuum can reach speeds greater than those achievable inside a crystal and the voltages that can be managed are greater for the same size of devices [10-11].
However, one of the problems that currently limits its development is the ability to maintain high vacuum conditions in the device, a problem that can probably be overcome by working either in low vacuum or by improving the encapsulation techniques of the devices [12-14].
Although there are interesting development possibilities and considerable progress has been made in recent years, we are currently still a long way from commercial production. However, techniques derived from those of integrated circuit production are already in use to produce new types of cathodes with advanced characteristics for use in vacuum tubes.

V. CONCLUSIONS

The history of vacuum tubes is very complex and in this article we have only presented a brief review. Several topics were left out, such as tubes for the acquisition and reproduction of images, which marked the birth of television, the production of long-lasting tubes used in the first computers, and several variations of microwave tubes. In some passages of history we have had to simplify, leaving out several intermediate steps and the various appeals to the courts for patent disputes. Many of the innovations in the history of vacuum tubes were intertwined with the personal adventures of the inventors, as in the case of the spouses O. Heil and A. Arsenjewa-Heil. It is clear that vacuum tubes have faced strong competition from solid-state devices and integrated devices and have disappeared from the eyes of the general public except for microwave ovens. However, they have managed to resist in high power and high frequency niche.
The coupling of electron beams to electromagnetic waves allows these devices to work up to millimeter waves.

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