The End of Thermionic Valves?

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Introduction: The aim of this paper is to investigate the invention and early development of thermionic valves, the applications they are still used in at present and whether they will continue to play an important role in the future. After more than one hundred years of valve history, thermionic valves have been replaced from many of their traditional applications by smaller, cheaper and better devices. Moreover, new technologies are being constantly developed to achieve better power and economic performance. Therefore, we need to consider three questions. Firstly, are valves going to remain in the present widely used fields, like the magnetron? Secondly, is it possible that valves can be applied back to their traditional fields by improving their performance? Thirdly, in what new areas could the thermionic valve be used for in the future?

Contents

The birth of electronics as a branch of engineering that exploits the controlled flow of electrons to handle information or energy transmission is closely related to the invention of thermionic valves in the early years of the 20th century. However, before we can review the development of this technology, let us briefly look at its basic structures and operating principles.

The Structure of Thermionic Valves

Thermionic valves (also known as vacuum tubes) usually consist of the following components:

- Cathode (K).
- Anode (P), also known as the plate.
- Control Grid (G).
- Filament (F), sometimes called the heater.

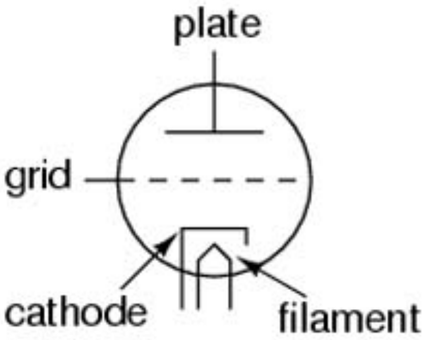

Figure 1: Circuit diagram of a triode with external heater [1]

During operation, the cathode emits electrons towards the anode (which is usually held at a much higher potential than the cathode). The filament is a piece of fine wire usually made of tantalum or tungsten. The cathode is heated up so that electrons are released through the process of thermionic emission. The control grid is made of a spiral of fine wire, thus allowing electrons to pass through the grid without colliding into it. It is placed between the anode and the cathode, closer to the latter. By varying the voltage applied to the grid, the electron flow from the cathode to anode can be controlled [2].

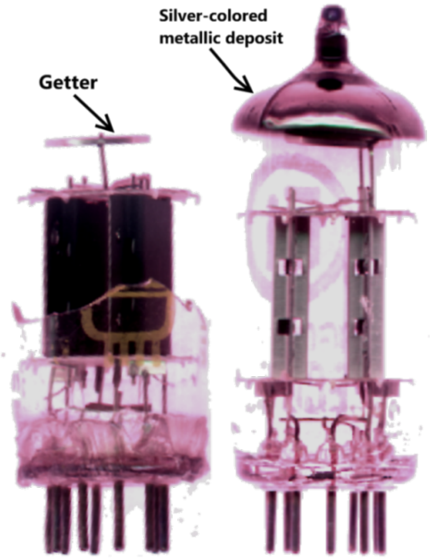

Figure 2: Getter diagram made by Oliviosu, modified by Qinxin Liu [4]

In order to obtain a hard vacuum inside the tube, a modern tube is always constructed with the degassing agent, *'Getter'* [3]. A getter is generally made of active metals such as barium, aluminium and magnesium alloys. After pumping out the air, the getter is heated by the RF induction. It absorbs the remaining air to form a silver coating on the glass. If the tube is broken or is leaking air, the silver coating will fade away. Disappearance of the silver coating indicates the vacuum tube can no longer be used.

In a self-heated tube, the cathode is able to heat itself up and emit electrons as a result. This configuration has no external filament, so the cathode is sometimes called a filament as well. In this case the cathode has two terminals (F' and F) and usually requires a low voltage across and large current through it. As a consequence, this process consumes a large amount of power [5].

Since the tube is highly vacuumed, the heat generated by the electron ejection on the plate can only be dissipated by radiation or through the metal-glass junctions. In order to radiate more power, plate surfaces are usually made less glossy and darker.

The three electrodes, cathode (K), anode (P) and grid (G) of the triode vacuum tube resemble an NPN semiconductor transistor's three terminals, emitter (E), collector (C) and base (B) respectively. They have very similar behaviour that will be covered in the section below.

Principles of operation

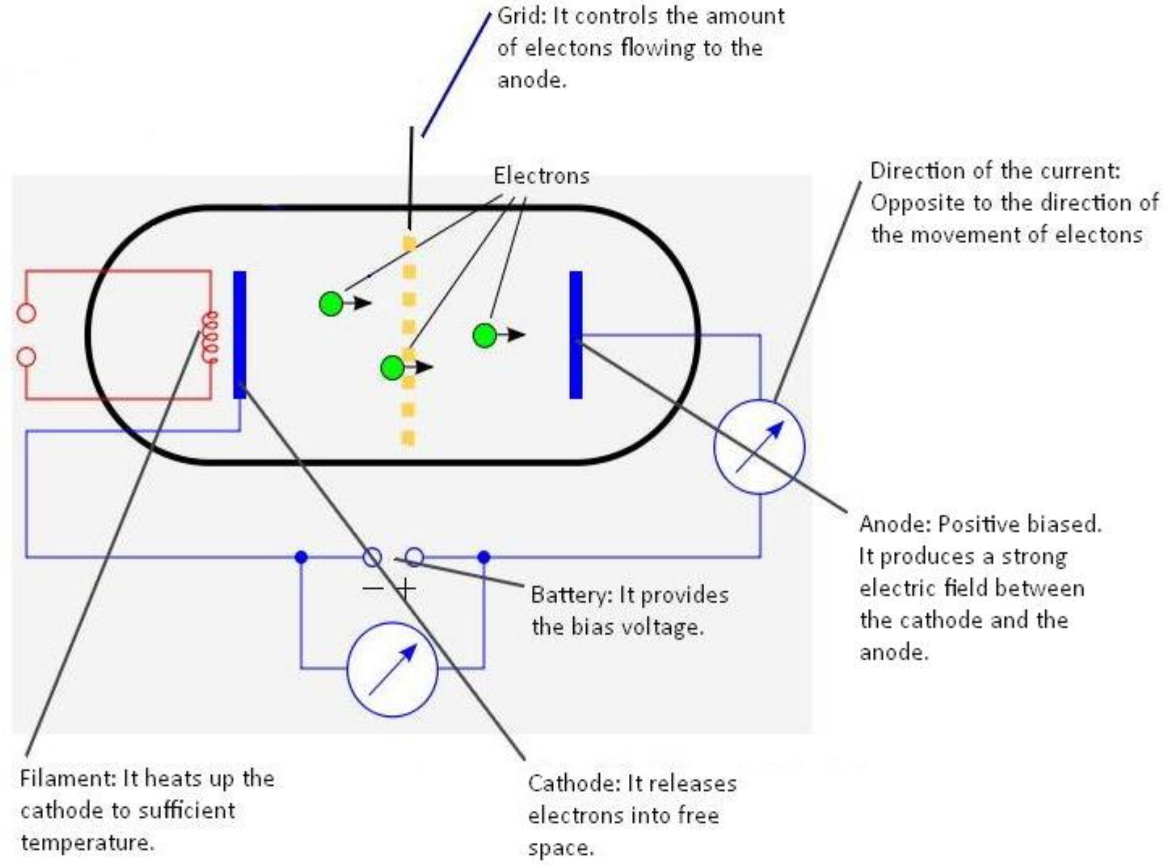

Figure 3: Operation of a diode made by Sany Fu modified by Qinxin Liu [6]

Diode

Inside a diode, the cathode is heated up by the filament to a sufficient temperature at which it releases free electrons into the space around it. These free electrons are then pulled towards the anode by the electric field between the cathode and anode. The electron stream can only flow from the cathode to the anode and the reverse is impossible since the anode does not emit any electrons. The rate of electrons being released by the cathode is given by the Richardson's equation of thermionic emission [7]:

$$J = A_G T^2 e^{-W/kT}$$

- J the current density with SI unit A/m^2
- T is the temperature of the cathode in Kelvin
- W is the work function of the metal cathode
- k is the Boltzmann constant
- A_G is given by $A_G = \lambda_R A_0$, where typically $\lambda_R A_0 = 0.6$ A/m^{2}K^2

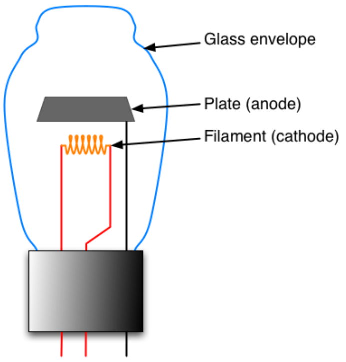

Figure 4: The structure of a diode [8]

Moreover, the current drawn by the anode (the plate current) is given by the Langmuir-Child equation of space charge [9]:

$$I_p = G\,(V_p + \mu V_g)^{3/2}\ ,$$

Where I_p is the anode current, V_p is the anode voltage, V_g is the grid voltage, and G is a constant depending on the structure of the electrodes.

Therefore, the current saturates when the anode voltage is high enough that the anode attracts all the electrons released by the cathode. This does not occur during normal operation for a triode (discussed next).

Triode

A third electrode, grid (G), is introduced inside the tube. It controls the plate current by applying different bias voltages on it. When negative, it repels the electrons coming from the cathode by producing an opposing electric field against the anode. As a result the current flow between the anode and the cathode is reduced. In this case, the grid draws no current. When a positive voltage is applied, however, it enhances the electric field so more electrons can reach the anode. Now the grid draws a small current itself but it is considered negligible. In order to limit the plate current, so it never reaches saturation, the grid is usually negatively biased. The grid sensitively controls the large plate current by drawing a small but negligible current, so it makes the vacuum tube a very powerful current amplifier.

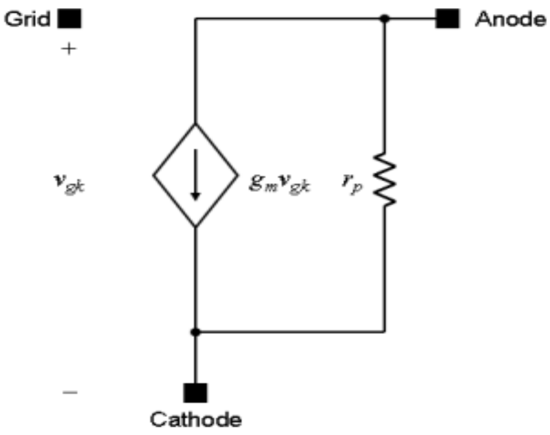

Figure 5: Small signal model of triode [11]

The small signal model of a triode is quite similar to a MOSFET. Instead of the Gate, Source and Drain, the triode has a Grid, Cathode and Anode. By analysing the circuit we can easily derive the maximum (unloaded) voltage gain, $\mu = g_m r_p$ (where g_m is the transconductance and r_p is the plate resistance) which is exactly what we have for the voltage gain of a MOSFET ($|A_v| = g_m r_o$) [10].

A typical triode, the 6J5 for instance, has a μ of 20, g_m of 3.0mS and r_p of 6.7kΩ. As compared to a transistor, the transconductance and the maximum voltage of a triode seems a lot smaller. However, the triode is a very good power amplifier as the grid can control a large current using negligible power.

The History and Development

In 1883, Thomas Edison, in his attempt to improve incandescent lamps, inserted a metallic plate into an evacuated tube and observed that a current flowed between the electrode and the filament when a positive voltage was applied to the electrode. When a negative voltage was applied, though, no current flowed. This would come to be known as the Edison effect. Thus, a thermionic diode was invented, however it was initially only used as a regulator of voltage across the filament of incandescent lamps [12].

John Ambrose Fleming studied the Edison effect and mentioned the rectification of low-frequency signals by the thermionic diode in his paper as early as in 1890. When he was later involved in the radio transmission experiments carried out by Marconi Wireless Telegraphy Company, he realised that the rectifying property of the diode could be used in the detection of high frequency radio waves and got a patent in 1904[13].

The detected signals were still quite weak, and long distance communication became possible only with the invention of the triode by Lee De Forest in 1907. He showed that inserting an extra grid into the tube provided control of the current flow between the cathode (filament) and the anode (plate). This device, called ‘Audion’ by Lee De Forest, was the first electronic amplifier and was used for detection of high frequency oscillations. The Audion was quite a sensitive detector, however its operation was not stable because it contained some residual gas. As it is shown in the characteristic of the Audion (figure 6), at a certain anode voltage there is a rapid increase in the anode current due to the onset of ionization of the residual gas; hysteresis is also explained by poor vacuum conditions. Because of the gas discharge, the sensitivity of the Audion decreased over time and it had to be readjusted [14]. The triode was first used as an amplifier by Lowenstein in the USA and later in 1912 De Forest was able to use a three stage Audion amplifier to get a gain of 120 [15]. Around 1913, it was realised that feedback could be used to make the triode into a better amplifier of high frequency signals or a generator of oscillations.

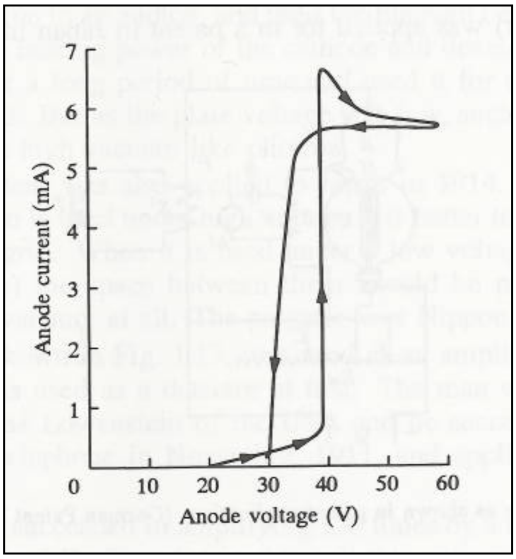

Figure 6: An example characteristic curve of an audion [16]

Under the impression that the residual gas was important in the operation of a thermionic valve, Lieben and Reisz developed a gas discharge tube in Germany in 1910, which is considered to be the first thyratron. Mercury vapour was sealed inside the tube and the cathode contained calcium oxide [17]. The thyratron, a high current and low-pressure tube, was later developed by Albert Hull. This invention was the origin of controlled electronics.

In the decade following the invention of the thermionic valve, there was a controversy in the understanding of its operation. As the vacuum techniques were poor at that time and many experiments were not repeatable, some scientists believed that thermionic emission depended on the chemical reaction between the ionized gases and the oxide cathodes, whereas others considered thermionic emissions to be the fundamental property of metals. This controversy was resolved by Irving Langmuir, who managed to get a rather low vacuum and using Richardson’s theory of thermionic emission, showed that the anode saturation current is limited by the space charge effect and that the relationship between the anode current and the anode voltage obeys the so-called three-halves power law [18]. This work, as well as the advances in pumping techniques, led to large scale production of high vacuum three-electrode receiving tubes during World War I. Subsequently, radio receivers based on thermionic valves that acted as rectifiers, were able to replace their predecessors that used galena crystals.

At the same time as Langmuir developed his hard tube at General Electric, Harold Arnold used a rather high vacuum triode in the repeater for telephone communication between New York and San Francisco in 1914. Not only was it the first time the triode was used for practical purposes, but also oxide-coated cathodes were introduced both by Langmuir and Arnold, which greatly increased emission and therefore enhanced the anode current. Langmuir used a thoriated tungsten filament whereas Arnold put barium oxide on platinum wire. These oxide cathodes later became very important for high-power transmitting tubes [19].

By the end of World War I which boosted the production of vacuum tubes for military uses, their operation had been thoroughly described. The annual production of electron tubes reached 300,000 for France, Britain and Germany by 1918 [20]. Stability of operation was a major requirement so soft vacuum tubes went entirely out of use. Valves could now be designed for particular purposes by modifying their internal structures and physical characteristics. A few discoveries played an important role in this. Firstly, it was realised that the cathode current depended on the space charge, which was determined by the electric field induced by the grid and anode voltages. Secondly, amplification constant **μ** was introduced. The most successful wartime tube is the so-called 'French' valve developed by Ferrié. It consisted of a spherical bulb in which a straight tungsten filament, a helical molybdenum or nickel grid and a cylindrical nickel anode were arranged horizontally. It was widely used in receivers by the Allied armies [22].

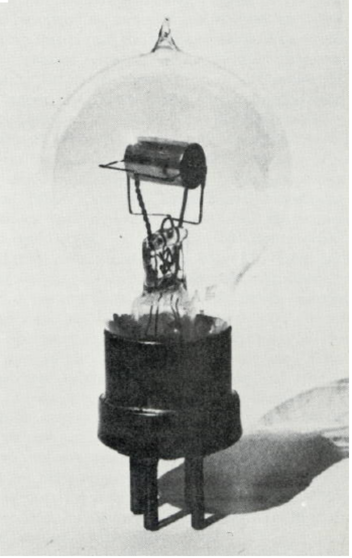

Figure 7: The 'French' valve

With the triode, communication techniques and broadcasting developed to a huge extent, but it had its limitations. The grid-anode capacitance caused coupling between input and output and limited operation frequencies. As shown by A. Hull in 1926, inserting a screen grid between the control grid and the anode could lower this capacitance. Prior to this, Schottky suggested a four-electrode structure in 1916, but his aim was to increase the amplification factor [23]. This type of tube was logically named the tetrode. The grid was usually held at a constant positive voltage and bypassed to the anode by a capacitor. By shielding the control grid and anode, it minimized the undesired feedback and oscillation hence reduced the capacitance between them (from 5pF down to about 0.01pF). It also increased the plate resistance (reaching 1MΩ). As a result, the maximum voltage gain increased and the high-frequency gain also improved.

The tetrode had a disadvantage, secondary electrons emitted from the plate by the bombardment ceased to return to the plate but were attracted by the screen grid when it was at higher potential than the plate. This phenomenon resulted in the disruption of the linear relation between anode current and anode voltage, narrowing the range of operation. Moreover, when the grid current formed by the secondary electrons gets high enough, it will damage the grid causing it to melt down. A third grid, the *suppressor*, held at zero or negative potential between the screen grid and the anode was suggested by Tellegen and Holst of Philips Company in 1926, making up the configuration of the pentode [25].

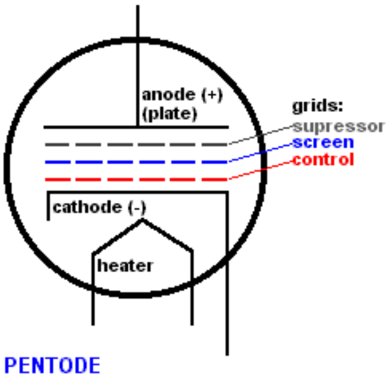

Figure 8: Circuit diagram of pentode showing the three additional grids used [24]

With the pentode, the thermionic valve obtained its final form. Hexodes, heptodes and octodes which followed did not introduce any particular new physical principal but rather combined functions of different tubes under one glass envelope. An example is the pentagrid converter type 2A7 developed by the company RCA in 1933, which was used for frequency conversion in superheterodyne radio and television receivers. In this tube, all the elements were located in a radial manner around the cathode in the following sequence: oscillation grid, oscillation anode, first screen grid, control grid, second screen grid and anode. The cathode, oscillation grid and oscillation anode composed the triode used for local oscillation; the generated AC voltage signal was coupled to the control grid where it is mixed with the input radio signal. The difference between the generated signal and the input signal gives the output signal of the intermediate frequency which is more convenient to process. The same tube could be used to provide gain control of the mixer stage, so that the output is not distorted when the input signal is too strong or too weak. This is known as 'variable-**μ**' operation and is achieved by applying two separate voltages to the control grids [26].

Early computers and the invention of the transistor:

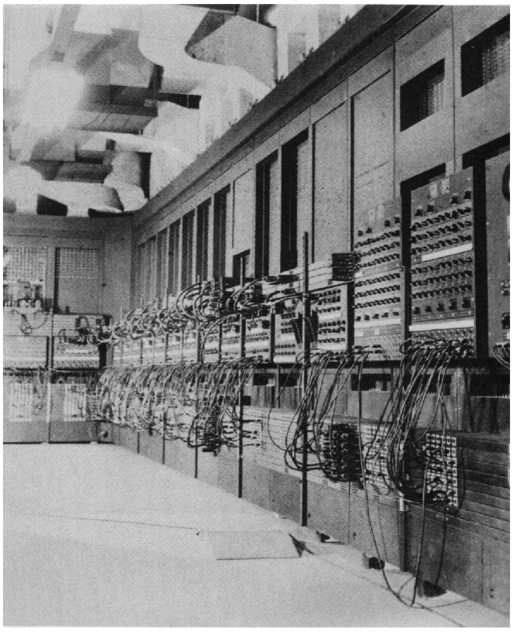

Figure 9: The ENIAC computer employed vacuum tubes, in addition to occupying 170 square metres [30]

Up to the period we have so far examined, vacuum tubes had clearly been developing at a rapid pace. This resulted in increased functionality that directly led to tubes being used in more and more applications. In 1946, one of the first major electrical computers, ENIAC (Electrical Numerical Integrator And Calculator), was built. It was funded by the US military, who planned to use it to calculate complex artillery-firing tables to improve the accuracy of their weapons. The computer employed almost 20,000 valves and was able to perform calculations considerably faster than earlier mechanical models [27]. Valves had played a significant part in yet another important application. However, the ENIAC had several major problems that were closely tied to the valves it employed. These included its incredibly large power consumption (160kW) and physical size (it weighed 30 tons) [28]. These disadvantages, in addition to frequent maintenance it required to remain operational, strengthened the interest in alternative devices that could fulfil the functions of tubes more effectively. This directly led to the eventual invention of the transistor in 1947 [29].

Although tubes would still be widely used for several more years, transistors had several advantages over their valve predecessors that clearly made them more suitable for certain applications. These included their small size, lower possible operating voltages, lower power dissipation and no warm-up period. All direct results of the transistor not having to rely on wasteful heating to begin conducting [31]. These in addition to the invention of the integrated circuit, a method that would allow more and more transistors to be packed onto a small chip, meant that valves were completely replaced in the field of computers [32]. The application of tubes in computers in the late 40s and early 50s corresponds to their peak usage. In the years to follow, leading to the present day, valves would be slowly replaced by the transistor. However, as we shall see in the next section, despite being less visible in our day-to-day lives, tubes presently still play an important role in several applications.

Present Day Thermionic Devices

Following on from the past, thermionic devices have held some stead into present day despite competing technologies such as the silicon transistor often taking their place. However, while its applications in computing have for the most part ceased to exist, thermionic valves still have distinct advantages over newer technologies in certain applications. The majority of current uses are continuations of its uses in the past that, generally speaking owes to the reliability and high power usability, which their transistor based counterparts cannot efficiently match.

Thermionic devices have practical value in the present day; for example, the X-ray tube is used in a host of applications, from airport to medical scanners. They have also long played important roles in scientific research such as particle acceleration, integral to the furthering of modern science. These will both be looked at in greater depth later.

Furthermore, radio frequency broadcast effectively utilises their high power advantages and must often operate at high powers in order to give large geographical spread. Multi-staged transistor amplifiers for radio broadcast may be sufficient up to approximately 20kW [33]. Scaling transistor amplifiers to higher powers proportionally increases the complexity of the system and solid-state dissipation also increases. Vacuum tube technology on the other hand can be physically scaled up, without increasing the core complexity of operation. As output increases, the efficiency becomes much more attractive as a much lower proportion of the energy is lost as heat to achieve thermionic emission. The implications of this are that high-powered vacuum tube based transmitters are vastly superior to transistor-based solutions. The BBC uses some very high-powered transmitters to broadcast radio and television in central parts of the country, which can be found to output 100kW up to 1MW [34]. The highest powered vacuum tube which exists today is the Eimac 8974 (a tetrode) which is able to dissipate 1.5MW; physically large and water cooled, it is used only in commercial broadcasting and military applications [35].

Military applications favour vacuum tube technology for their high power characteristics for use in radar as well as an apparent natural tolerance to electromagnetic pulses, which occur during nuclear explosions as well as environmental variations due to solar emissions [36].

Sound Applications

Perhaps a more curious application of vacuum tubes is its application into sound amplification. Sound, like taste, is viewed as subjective so one cannot solely use empirical quantification as evidence for the use of vacuum tubes in many modern amplifiers for musical instruments. Around the late 1940s and early 50’s originated the genre of rock and roll, with electric guitar as lead instrument, vacuum tube amplifiers were very much a part of their distinctive sound. Of course, at the time they did not have the choice of using transistor amplifiers, however, modern musicians today still very much desire the original tones created back in 50’s achievable using vacuum tube based amplifiers.

There is strong debate concerning the favourability of either type. A very significant number of people believe valve technology produces much clearer tones. Looking at specifications of high-end models actually yields very similar operating characteristics. The audible difference has been shown to possibly manifest in the different harmonic responses when over driven.

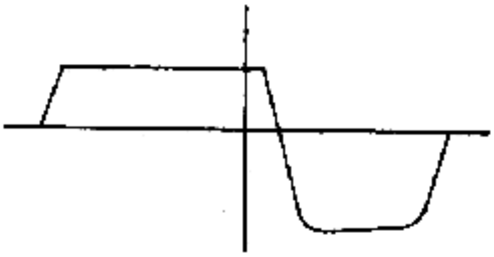

Figure 10: Waveform of triode amp at 12dB overload ,1000Hz tone [37]

Valve amplifiers seem to clip much more favourably and smoothly than transistor types (figure 10 illustrates a response that exhibits softer clipping). Depending on which harmonic distortions are most dominant, over drive will cause varying tonal modifiers. Transistor amplifiers give off strong 3rd and 5th odd harmonic tones, which have a blanket and metallic effect respectively [38]. Valve amplifiers tend to have dominant even harmonics producing “choral or singing sounds.” These are generally accepted as much more pleasant distortion characteristics, preserving clarity further than odd harmonic dominance.

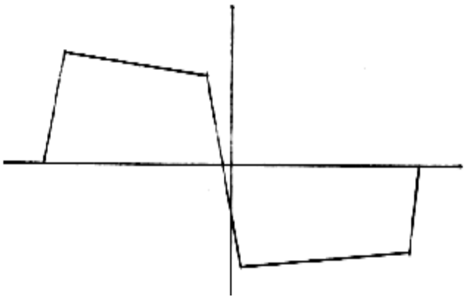

Figure 11: Waveform for transistor amp at 12dB overload, 1000Hz tone [39]

Distortion is so often apparently, either on purpose or undesired, that valve-based amplifiers may be thought as more flexible to real life conditions than transistor based types. Only when both are kept in linear regions are they for the most part equal. Valve amplifiers have a great shortfall it that the transformer circuits are extremely expensive [40]. This is for the most part eliminated in transistor-based designs. The consequence of this is that vacuum tube variants do not exist in the low to mid priced range and for this reason alone they have been mostly replaced by solid state in mainstream consumer applications.

The Magnetron

A magnetron consists of two parts: the tube core and an electromagnet.

In the tube core, the filament (cathode of the tube) is carefully sealed into the tube and is placed at the centre of the magnetron. The anode is a hollow cylinder of copper, which surrounds the cathode and the tube core (figure 12).

A magnetic field is provided by an electromagnet in parallel to the filament, hence when the electrons are accelerated from cathode to anode,

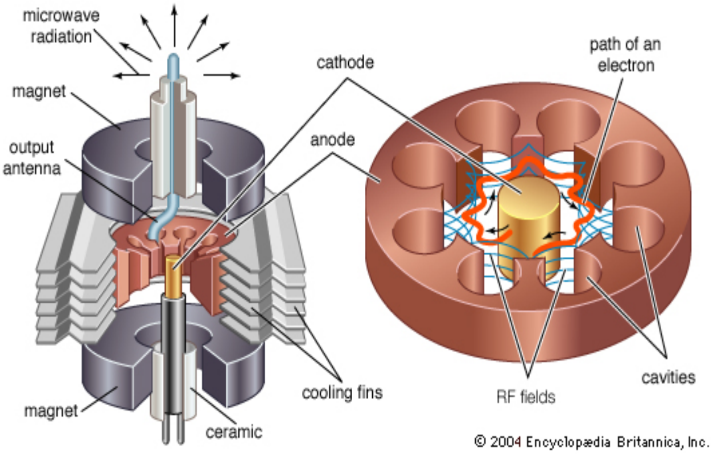

Figure 12: Structure of magnetron [41]

they spiral outward in a curve rather than moving directly to the anode.

The anode block of the tube includes many cylindrical cavities (figure 12), which each serve as a resonant RC (resistor-capacitor) circuit, causing electrons to bunch into groups. An antenna will transmit a part of this RF (radio frequency) energy [42].

Magnetrons in microwave ovens:

The microwave oven is one of the most widely used household appliances. The reason for its popularity is its ability to heat food quickly and efficiently. The magnetron is the heart of every microwave oven. As its name suggests, microwave ovens use non-ionizing microwave radiation to heat food. In order not to interfere with radar and other communication systems, the frequency of microwaves generated by the oven is usually designed to be 915MHz or 2.45 GHz [43].

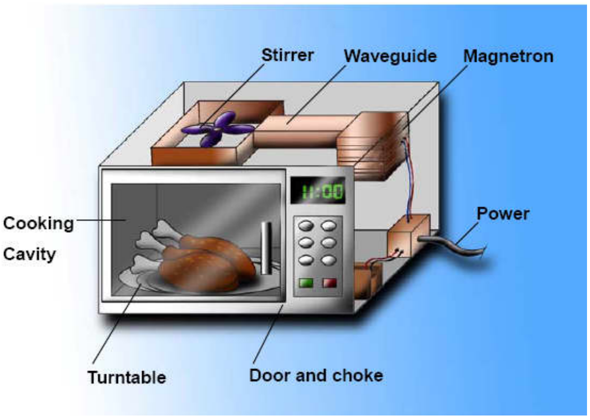

Figure 13: The structure of a Microwave Oven [44]

The transformer in the oven raises the 220V household voltage to 3,000V or more and delivers it to a magnetron. The magnetron generates microwaves, sending them through a waveguide into the cooking cavity. The stirrer at the end of waveguide distributes the microwaves evenly [45]. Not everything is heated in the microwave oven, only molecules that are electric dipoles (a polar molecule with equal and opposite electric charge) such as water, sugar and fat, will absorb energy from the microwaves. As the microwaves consist of oscillations of electric and magnetic fields perpendicular to one another, electric dipole molecules tend to align themselves with the electric field because they have positive and negative charges on opposite sides. The electric field in microwaves reverses billion of times a second, causing the molecules to rapidly turn back and forth, collide with one another and hence produce heat quickly. The effectiveness and convenience of the microwave, in addition to the lack of competing technologies, almost ensures its continued use in the future.

Cathode Ray Tube (CRT)

A simple CRT mainly consists of an electron gun (which includes an accelerating electric field), deflection coils, a shadow mask and a fluorescent screen (figure 14). It is used to create images, widely applied on display devices such as televisions, oscilloscopes and computer monitors. However they have gradually been replaced by liquid crystal (LCD) and plasma displays in many applications.

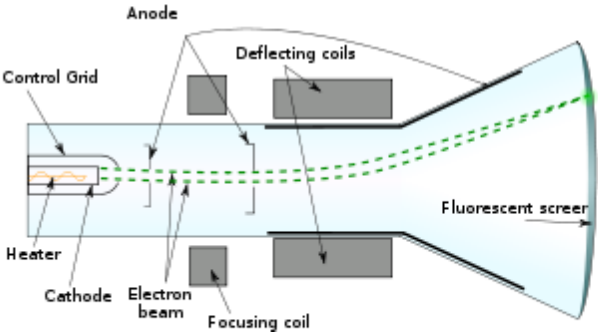

Figure 14: The structure of a Cathode Ray Tube [46]

An electric field is placed in front of the electron gun and is used to accelerate the electrons emitted by the electron gun. The deflecting coils impose an adjustable magnetic field that is perpendicular to the electric one, thus allowing it to control the path of the electrons by varying the magnitude of the magnetic field. The image will appear when electrons hit the phosphor screen.

Applications:

The television set (or computer monitor) is one of the main applications of CRT. However, by 2008, although CRT TV and computer displays were still used in developing countries, they had almost disappeared in the developed world. The liquid crystal displays have become more and more popular in recent years. By comparing these two competing technologies, we can begin appreciating why this is the case as well as determine whether CRT will continue to be employed in future. The following characteristics will be used for our criteria.

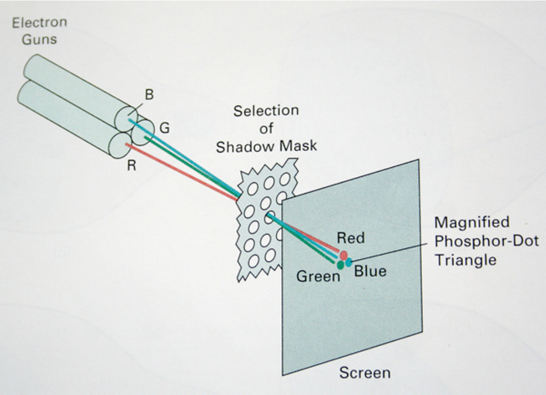

Figure 15 Imaging principle of CRT [47]

- Resolution: A colour CRT display has three electron guns and three different phosphors on the screen which emit red, blue and green light respectively. A metal plate with tiny holes is placed in front of the fluorescent screen to ensure that the electrons from each gun strike the corresponding monochromic phosphor. This metal plate is known as shadow mask. The distance between holes on the shadow mask is called dot pitch, which determines the maximum resolution of a CRT display. (The dot pitch is the distance between a dot and the closest dot of the same colour on a colour CRT.) The smaller the dot pitch, the more pixels the screen can accommodate, hence the higher the resolution. A CRT can display an image with any resolution lower than the maximum dot pitch defined resolution, as the electron gun can flexibly make adjustment [48].

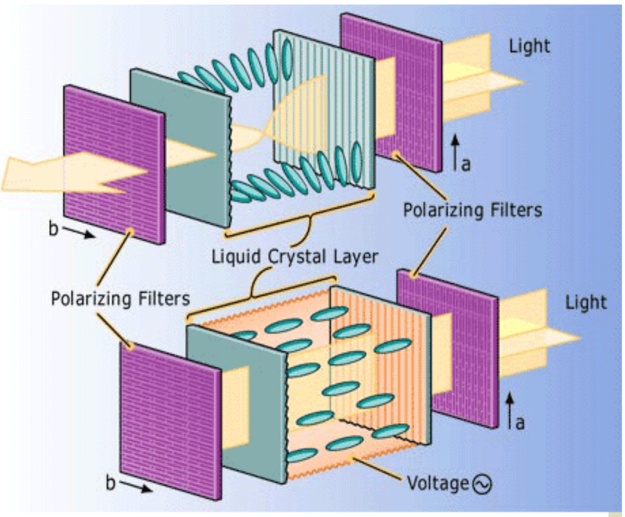

Figure 16: The process that the liquid crystal rotates the polarised incident light [49]

- For LCDs, on the other hand, the pixels have a layer of liquid crystals aligned between two electrodes and two polarising filters that are perpendicular to each other. Under a control signal, the liquid crystal molecules twist themselves to reduce the rotation of the polarization of the incident light in different levels to pass light through the second polarizing filter. Hence the image appears on the screen. The imaging principle of LCD determines that for a fixed size of screen, the pixel arrangement is only suitable for image (signal) with a particular resolution (native resolution). Once the resolution is changed, the image on an LCD will be distorted [50].

- Refresh rate: For CRTs, the refresh rate is commonly referred as vertical scan rate. Corresponding with it is the horizontal scan rate. Horizontal scan rate is the time taken for the electron beam to travel from the left side of display to the right and back and therefore describes the number of horizontal lines displayed per second. The CRT must scan vertically one horizontal line at a time; one entire completion of the screen is called a refresh. This is where the term refresh rate comes from. Clearly, the total number of pixels within a display determines the refresh rate- the higher the resolution of display, the slower the refresh rate. LCDs are significantly different in the way they refresh, however. Firstly there are no black states due to existence of a backlight and the LCD will refresh all at the same time unlike the scanning method CRTs employ. This means LCDs cannot flicker, instead refresh rate is important in determining how smoothly motion is displayed. Generally speaking, a CRT refresh rate must be higher than an LCD to maintain a comfortable viewing experience (approximately 85Hz on CRT or 60Hz LCD) [51].

- Response time: is the minimum time to change a pixel's brightness. Because of its imaging principle the CRT maintains a high frequency of impact between electrons and fluorescent screen to form a static image. For this reason, response time could be said to be limited by refresh rate/scan rate as actual response time for each pixel is almost instantaneous (order of a magnitude faster than LCD). For LCDs, although the response time continues to reduce, high quality colour reproduction panels (non twisted nematic) have relatively slow response times (8-16ms) [52]. This can cause smearing around fast moving objects (known as ghosting), which makes the LCD somewhat unacceptable for fast moving video.

- Other issues: LCDs have absolute advantage in terms of volume. The thickness of an LCD will only be a few centimetres no matter how big the screen is. But for CRTs, the larger the screen, the greater the volume will be occupied because of its imaging principle requiring the projection of the electron beam. This has proved a crucial commercial factor, as most consumers prefer the less obtrusive LCD, despite the CRT providing superior viewing in many respects.

- For CRTs, there exists a controversy on the emission of radiation. While small as most is filtered, there is some X-ray radiation emitted. Unlike CRTs, the light source of LCDs can be made up of incandescent light bulbs or light-emitting diodes. LCDs consequently do not emit any ionising radiation.

CRT technology is seen as evolution of the vacuum tube and takes an important place in widespread household technology. While gradually being superseded by LCD technology due to practical issues such as size, CRT has held some distinct advantages, which for some time, gave scope for further evolutions of the technology. The most notable development was in the early 2000's where various companies came out with competing technologies to improve upon LCD contrast ratio and their inherent poor black levels due to the CCFL backlight required to illuminate the LCD pixels which themselves emit no light. Emerging technologies at the time included SED (surface conduction electron-emitter display), FED (field emission display, related to SED) and OLED (Organic Light Emitting Diodes) variants. SED based technology use large grids of nano-emitters as opposed to a single electron gun which is typical of CRT displays. This allows for the depth of the SED display to be similar to that of an LCD and each pixel may emit its own light allowing for much greater contrast ratios not achievable by conventional LCDs.

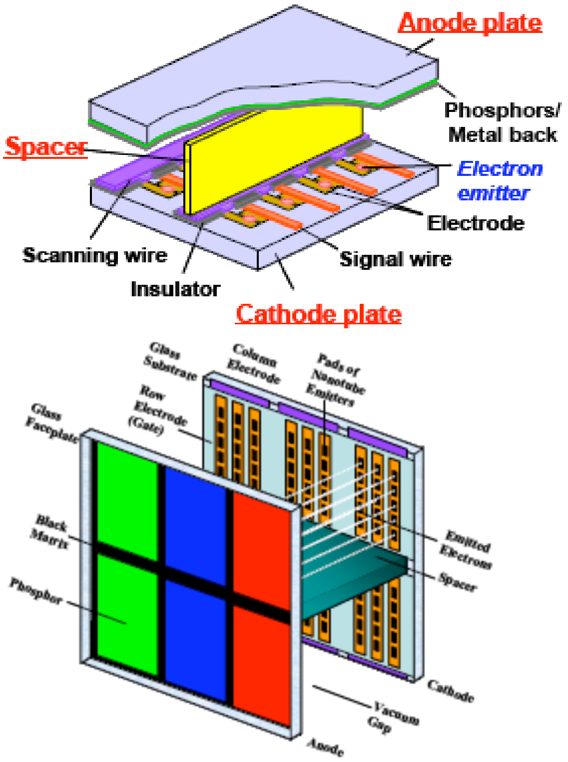

Figure 17: The structure of the SED (top) and FED (bottom). The two designs are similar except in their cathode design [54]

FEDs are similar but use different emitters of bundled carbon nanotubes (variations upon this technology are seen in the future section), this allows redundancy for defects due to the number of nanotubes in each bundle. Theoretically this would improve yields on a commercial manufacturing basis. SED are considered a more practical technology to FED as the technology allows greater gray scale uniformity [53]. FED's can only allow a few voltage cathode voltage levels, meaning that gray is realised using pulse width modulation of the emitters. Combined with un-linearity in emitter current, uniformity across the FED is usually poor, until the manufacturing process is improved to give greater control. As of today, both technologies have experienced manufacturing difficulties and failed to reach a commercially viable state before OLED became a natural successor. OLEDs now has most research and development from technology companies, they are able to operate without a backlight and can be made incredibly thin. They do however, suffer from degenerative effects thus have comparatively short life spans. Main developers of SED related technology such as Canon have stated that it has not disappeared entirely and may make its way into professional applications in the near future [55]. SED appears to be a case in which a good technology has not taken hold due to various external reasons, marking a major loss in the commercial future of thermionic technology.

Travelling Wave Tubes (TWTs)

TWTs are presently one of the most employed types of tubes. They are widely used in telecommunications, for instance radar systems and satellite transponders utilize them as amplifiers. According to recently published papers, solid-state power amplifiers (SSPAs) cannot compete with TWTs when it comes to outputting power in the megawatt region at frequencies in the range of 26.5 - 40GHz (Ka Band).

Furthermore, SSPAs only have an efficiency of about 15–20 percent whereas TWTs typically achieve 70 percent efficiency (figure 18). For satellite

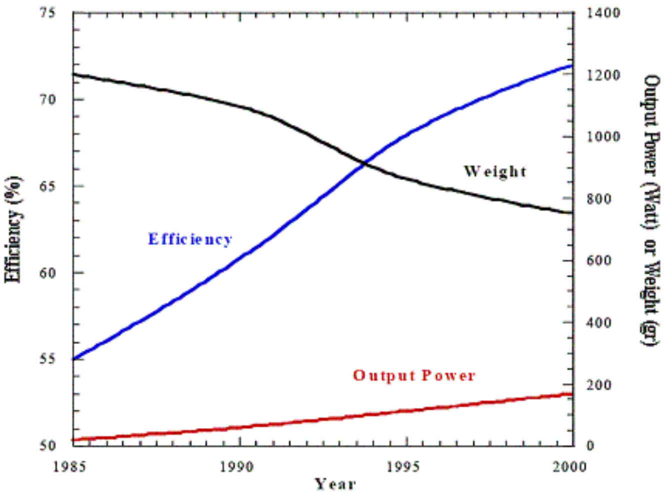

Figure 18: Graph illustrating TWT improvements in Efficiency, Output Power and Weight against Time [56]

transponders, where increasing the efficiency by 1 percent can potentially earn $30M more profit throughout its lifetime of about 15 years. As a result, they are certainly the only choice in the foreseeable future.

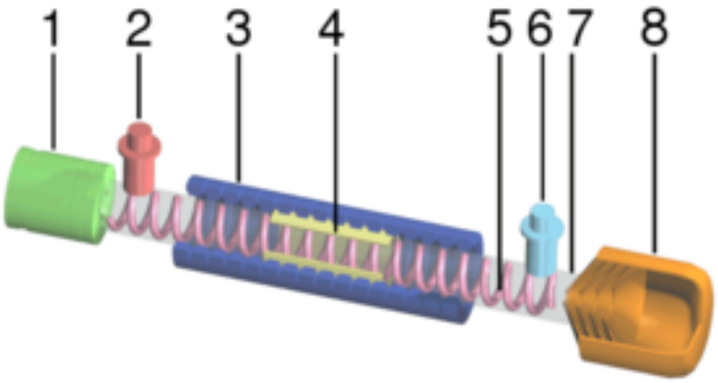

Figure 19: Cutaway view of a TWT [57]

1. Electron gun;
2. RF input;
3. Magnets;
4. Attenuator;
5. Helix coil;
6. RF output;
7. Vacuum tube;
8. Collector.

In a TWT, electrons are emitted by an electron gun at one end. As they pass through the tube, these electrons are accelerated and are focused into a beam before entering the tube. It then travels across the helix until it reaches the collector at the other end. A radio frequency (RF) signal is injected from the input, and propagates through the helix coil (known as a slow-wave structure) inside the tube until it reaches the output. The RF wave is able to gain kinetic energy from the electrons; in essence, it is amplified. The helix coil elongates the path the RF wave travels so it is able to synchronize with the electron beam. The current induced by the RF wave interacts with the electron beam, so it builds up the helix current as it travels through the tube. The amplified RF travels through the waveguide to the output at the other end of the tube closer to the collector. The attenuator is positioned in the middle of the tube to prevent the wave from travelling back to the input (figure 19) [58, 59].

Klystron

As compared to TWTs, klystrons, which represent another type of velocity-modulated vacuum tubes, have narrower bandwidth of operation but are capable of producing superior power. Invented by the Varian brothers of Stanford University in 1939, klystrons have been used extensively in radar equipment, telecommunications and particle accelerators.

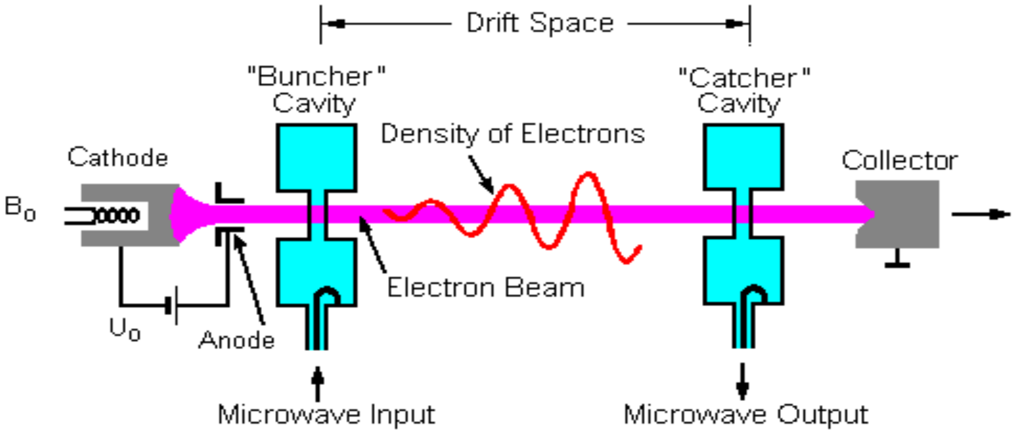

Figure 20: The structure of the two-cavity klystron [60]

In the basic configuration, the electrons are injected by the electron gun into an evacuated tube where they travel linearly towards the positive potential. The input microwave signal is applied to the input cavity, modulating the electric field around it. Depending on the frequency and magnitude of the signal, the electrons passing through the cavity are accelerated or decelerated, and as a result bunches of electrons are formed in the drift space. A standing wave of bunches of the electrons is produced in the output cavity, which location in the tube is related to the transit time of the bunches at the resonant frequency of the cavities. The magnetic field of the electron beam induces a voltage across the output cavity, which gives a linearly amplified microwave signal. Multiple cavities are used to improve the gain and efficiency of the klystron amplifier [61].

Klystrons are capable of producing high-power microwave output both for pulsed and carrier wave (CW) applications. The CW klystrons are used for ultra-high frequency television transmission and tropospheric communications such as air traffic and marine control (1-4 GHz). They are also employed in satellite-to-ground communication (4-12 GHz). With the increase in frequency, the operational power of CW klystrons decreases from about 50 kW to 1 kW. However, the pulsed klystrons used in radars and for driving RF linear particle accelerators can produce up to a hundred megawatts of power [62]. The combination of high power density and efficiency make klystrons, along with TWTs, the dominant technology in the microwave applications mentioned above.

The Future of Thermionic Valves

We have observed from previous sections that when first developed, vacuum tubes were used to perform a large variety of roles. However, the rise of more efficient solid-state devices subsequently led to their replacement from many of their original applications. More specifically, solid-state became and still is, the technology of choice when it comes to low power and low frequency amplification. However, as discussed earlier, tubes can match if not outperform their solid-state counterparts when it comes to high power amplification of high frequencies. Consequently a significant number of applications carry on using electron tubes and so whilst they are less visible in our day-to-day lives, they continue to play an important role in electronics by fulfilling increasingly specialised functions.

This section will try to predict what the future holds for this late 19th century technology and more specifically whether tubes will continue to fulfil the specialised roles they are used for presently. Additionally, we will also assess whether recent innovations in technology could result in new or improved types of tubes, which could have practical applications in coming years and thus leads a revival of sorts. After this analysis, we will be in a better position to answer the question raised by this report.

X-ray tube

The X-ray tube (figure 21) is another extremely important type of vacuum tube that still has many applications these days. Since Wilhelm Conrad Roentgen first discovered the X-ray, in 1895, they have been utilised in several fields that benefit society. As X-ray generators, X-ray tubes therefore fulfil important functions in many areas. However, it is important to note that their applications are still expanding. Consequently, despite it being more than one hundred years old, X-ray tubes are playing and going to play an irreplaceable role in many areas including medical and security scanners.

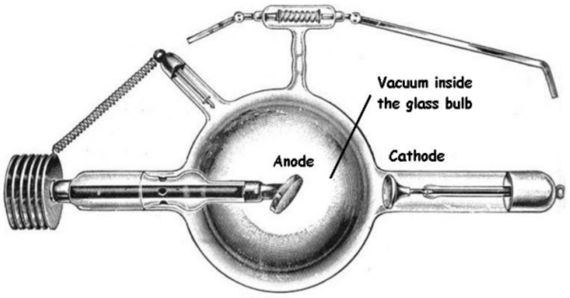

Figure 21: A Crookes X-ray tube from early 1900s. X-rays were first discovered in the late 1800s with such a device [63]

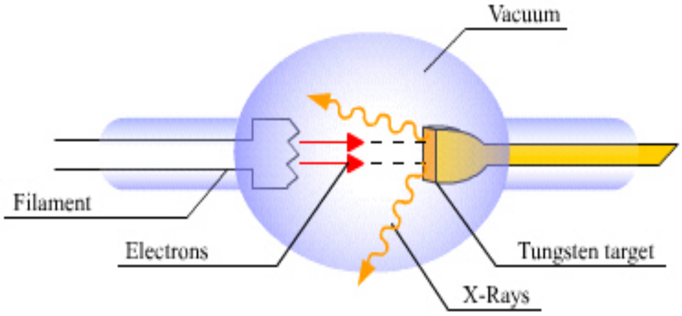

Figure 22: The operating principle of the X-ray tube. [64]

It seems easy to classify the X-ray tube as a vacuum tube from the structure. When we look into the process of how X-rays are produced, there is no doubt about the above assumption. As illustrated in figure 22, when the filament is heated to several thousand degrees, a large amount of electrons are released from the filament that accelerate towards the anode, which is usually made of tungsten. After the acceleration due to the potential difference of the filament (the cathode) and the target (the anode), the electrons will hit the other atomic particles of the tungsten target and rapidly decelerate. This effect produces Bremsstrahlung radiation, also known as 'deceleration radiation'; X-rays are generated from the anode. Of course, the anode and the cathode are enclosed in a vacuum tube to prevent the filament from burning up and to prevent arcing between the cathode and anode [65].

One of the most important usages of the X-ray tube in the medical area is the X-ray computed tomography (CT) (figure 23). CT is able to produce a large amount of data through a process known as "windowing", which is able to display various bodily structures based on their ability to block the incoming X-ray beams [66]. After that it can reconstruct images mathematically from this data and display them in a digital form. CT was brought into clinical practice in 1972 and has been showing a steady upward trend with respect to technology, performance and clinical use despite predictions and expert assessments that forecasted in the 1980s that it would be completely replaced by magnetic resonance imaging (MRI) [68]. Nowadays CT machines have become one of the most important medical instruments and are used in almost all hospitals around the world.

Figure 23: A computed tomography ct scanner [67]

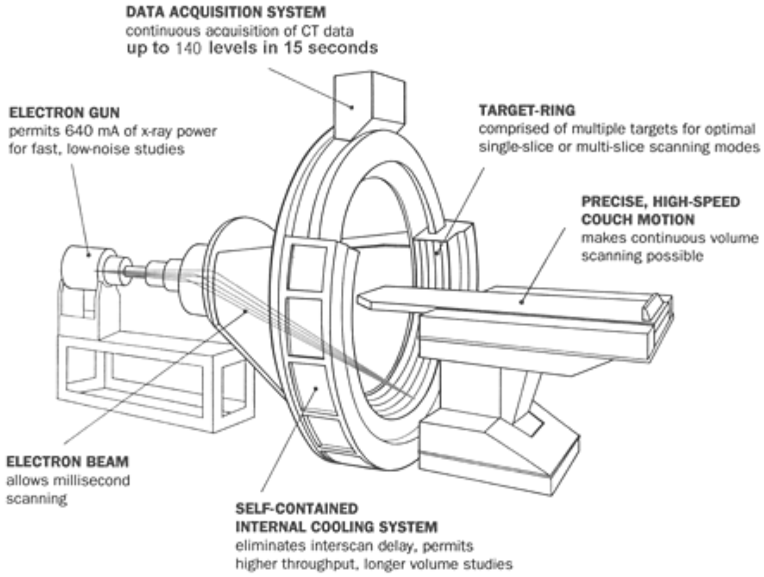

Figure 24: A description of CT constituent parts [70]

In figure 24, there is an explicit description of the CT machine. CT Scans are important because they simultaneously provide us with very detailed images of bones, different types of soft tissue and blood vessels. Since CT is less sensitive to patient movement than MRI and can be performed if the patient has an implanted medical device, CT will continue to do better than MRI in these cases [69]. They also allow us to look at very thick organs such as the brain, which are commonly scanned using CTs. As you can see from the figure, the electron gun can produce 640 mA X-ray beams for fast and low-noise studies through the target ring. The X-ray tube provides large power X-rays to scan the human body and no possible alternative sources have yet been proposed. Therefore, in the future we can see that the CT scanner will continue to play an irreplaceable role in the medical field. As a consequence, so will the X-ray tube.

Figure 25: A scan of a bag going through an airport security scanner [71]

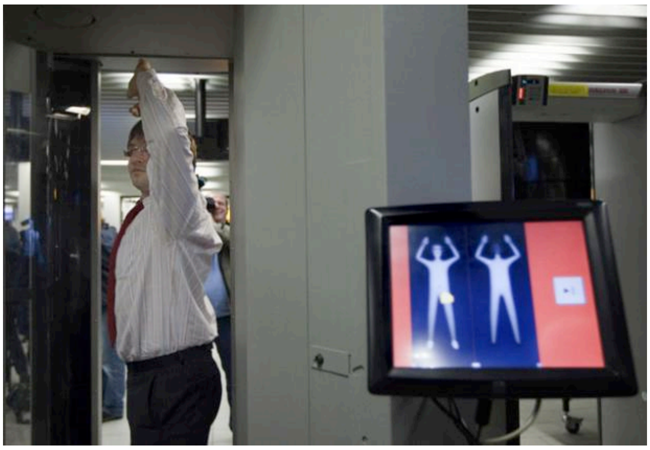

Figure 26: A body scanner being used to scan a passenger at an airport in America [72]

Another important application of X-ray tubes is in security scanners, usually used in airports. The X-ray produced by a prototype airport security scanner can show the shapes of objects in luggage and compare them with the weapon shapes in its database (figure 25). Recently, there has been a shift towards employing body scanners similar to those that scan passenger luggage (figure 26). Whilst there is a debate on the violation of privacy that would arise due to such scanners, it would undoubtedly help security guards to prevent people taking dangerous objects onto planes. Thus help avoid another terrorist attack like the 9/11 tragedy. Due to the turbulent social and political climate we live in today, there is a greater demand for improved security systems. This could result in widespread use of X-ray tubes as a result.

Using tubes for academic pursuits

As tubes are slowly replaced from many of their traditional roles, they continue to be utilised in an important and often overlooked field: academic research. Particle accelerators utilize klystrons, as mentioned earlier, that produce microwave radiation that energize particle beams. Accelerators have played and continue to play a vital role in answering some of the most significant questions of physics, because high-speed collisions result in particles breaking down into their fundamental components. Consequently klystrons still have an important application as high-energy RF sources as a result [73]. This is clearly illustrated by the active development of klystrons by Stanford Linear Accelerator Laboratories in America, who are planning to employ as many as 4000 in their latest accelerator [74]. What is also worth nothing is that there are plans to continue production into the future [75].

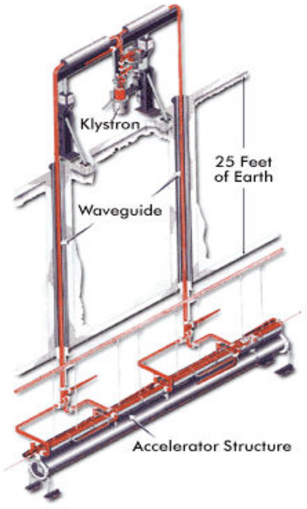

Figure 27: A klystron used in a Linear accelerator [76]

In addition to playing a secondary but significant role in accelerators, researchers have recently constructed specially built tubes that could further enhance our understanding of electron spin. The intrinsic quantum spin of electrons, a phenomenon that whilst too complicated for the scope of this report, can be thought to have two states, either up or down. Naturally, this property could be exploited to make a ‘Spin transistor’ [78], which, unlike modern solid-state transistors, would use the spin state rather than or in addition to the flow of electrons to represent information. The arrival of spin transistors could greatly enhance computer specifications- lower power consumption and increased information storing/transmitting capacity to name but a few [79].

However, plenty of obstacles need to be overcome before this technology can become a reality- namely a better understanding of spin-dependent phenomenon, in particular an understanding of the interaction of spin-polarized electron beams with solid-state structures. This is where custom-built vacuum tubes are playing a crucial role. Researchers have been able to study these subtle effects and have successfully constructed a ‘spin detector’ prototype [80]. The two setups used are shown below (figure 27).

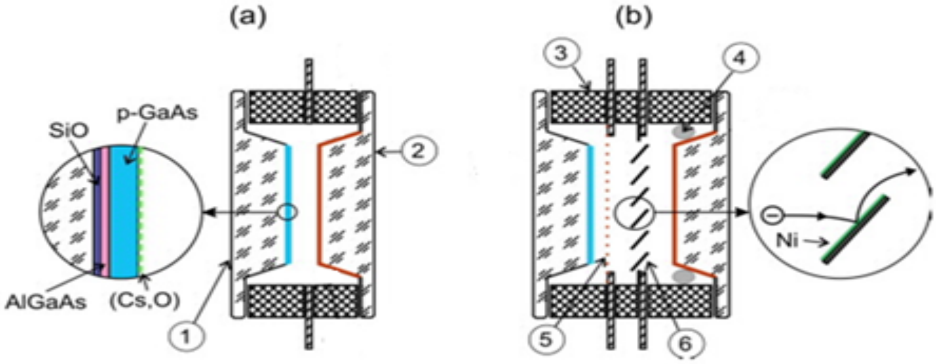

Figure 28: Custom built vacuum tubes. Setup (a) measures spin dependent photoemission. Setup (b) measures spin dependent reflection. 1) Photocathode unit, 2) anode, 3) metal-ceramic body, 4) non-evaporated getter, 5) copper micromesh, 6) Venetian blind dynode (emits secondary electrons). Both tubes are only a few centimetres in length and diameter. [81]

The first configuration was used as a vacuum photodiode that had a variable uniform electric field between its two plates. This allowed it to act as an energy analyser. The diode was able to determine the probability of photoemission from the semiconductor was linked to electron spin and the magnetic field it was placed in. As an energy analyser, the diode allowed the researchers to determine the magnitude and energy dependence of spin dependent photoemission. As a direct consequence of these findings, important semiconductor parameters such as the spin diffusion length could be calculated [82]. The second setup acted as a ‘spin filter’. By introducing a copper micromesh and venetian blind dynode, a device that upon being hit by electrons usually emits large numbers of secondary electrons, in this case actually only reflected electrons onto the anode depending on their spin state. This was due to the polycrystalline oxidized nickel layer added to the surface of the dynode. This filter could thus be considered a ‘prototype of a spin detector’, a device that has potentially large uses in many fields, including the novel field of ‘Spintronics’ (spin transport electronics), which unlike traditional electronics, places emphasis on the spin state rather than the movement of electrons [83].

These two setups were able to provide important results on the behaviour of spin-polarized electrons in semiconductor structures, in addition to making a spin filter, which could potentially have commercial applications. Whilst one can speculate about the significance and implications of these findings, or whether they will have any commercial applications in the near future, it is clear that these specially designed tubes were able to provide insight into electron spin. Vacuum tubes possess properties that make them ideal for studying the motion of charged particles; naturally an evacuated chamber allows electrons to travel reach high speeds, but compared to open set ups, contamination of components is also reduced considerably. This results in devices with significantly longer lifetimes [84].

This experiment, therefore, highlights more than anything the important contribution tubes are still making in academic research. They have quietly played a significant role in improving our understanding of particle physics, without receiving the credit they deserve. This is exemplified by J.J. Thompson’s monumental discovery of the electron, using tubes that he constructed [85]. Taking this into consideration, it is therefore remarkable, that over a century later that custom made tubes are again being used to further our understanding of electrons. This demonstrates that at the very least they may still have a role to play in future academic research.

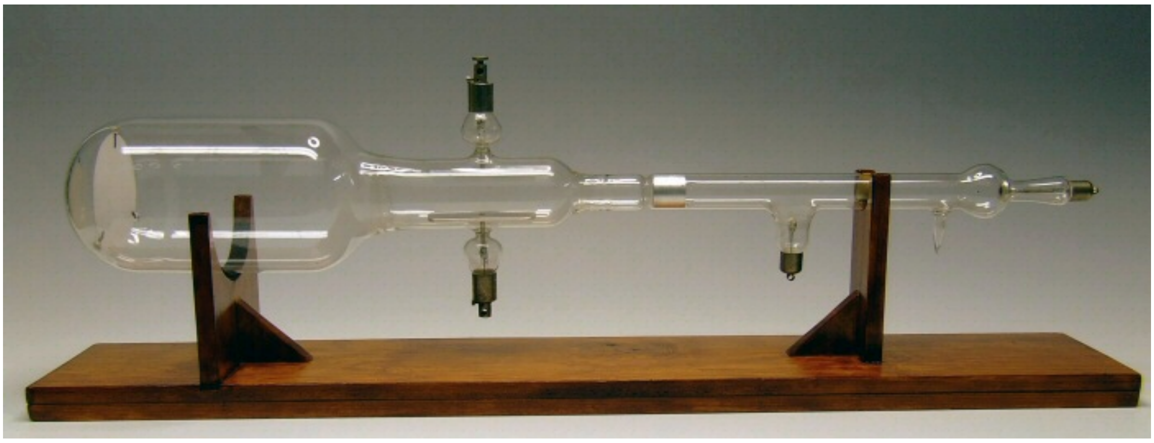

Figure 29: One of the vacuum tubes Thomson constructed that enabled the discovery of the electron. [86]

Cold Cathode valves using carbon nanotubes

Recent advances in 'cold cathode' technology may be able to overcome some of the deficiencies of traditional vacuum tubes, which for the most part, rely on thermionic emission to emit electrons. As discussed earlier, this process requires the cathode to be raised to 800°C or higher for emission to begin occurring and as a result has many associated disadvantages [87]. The most important of which is how it determines the size a tube can be shrunk down to; with the cathode at such high temperatures, there is a limit to how close you can place it to the grid and anode. A tube that employs a cold cathode (does not require heating), on the other hand, would be able to overcome these inherent disadvantages whilst maintaining high power capabilities. As a result, miniaturization would be possible, thus eliminating warm up times and allowing operation at higher frequencies (in excess of 10 GHz). Consequently, efforts were made by engineers and scientists to seek alternative emitters as early as the 1950s [88]. The arrival of solid state transistors clearly meant that traditional tubes would only be able to compete if they were adapted and therefore made the need for a different emitter more pressing.

Alternatives to thermionic emitters are tubes that rely on field rather than thermionic emission of electrons. Field emission can occur if a large enough electric field is present between the cathode and anode. A sizeable electric field is able to reduce the tunnelling barrier of electrons in the cathode and thus make it easier for them to escape [89]. However, to achieve this requires huge electric fields (in the order of GV/m) or very narrow emitters would have to be used (Fowler-Nordheim equation explains what factors field emission depends on). For the last four decades, Spindt-type field emitter arrays (FEA) have been utilised in several cold cathode tubes and whilst some of these tubes have been relatively successful, overall they have failed to live up to the large expectations that surrounded cold cathode emitters [91].

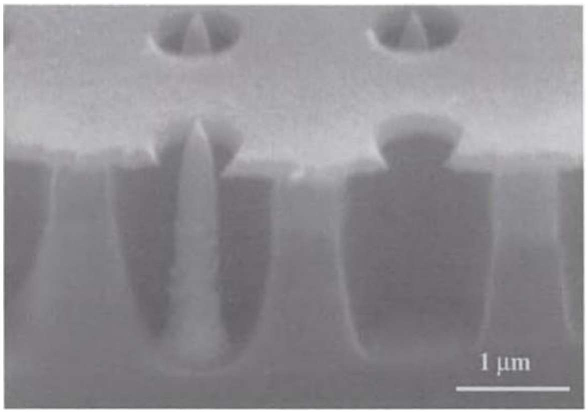

Figure 30: A scanning electron micrograph of a Spindt field emission array. Molybdenum metal cones act as emitters [90]

This is primarily due to the unreliability of these devices, which arises from existing micromachining techniques being unable to create hard enough vacuums for the device to operate reliably. As a result the tips are highly susceptible to poisoning over time [92]. Another major obstacle has been the inability to scale up; whilst one emitter can emit large current densities, an array of several thousand cannot produce the expected scaled up amount. This is due to an electrostatic screening effect adjacent tips have on each other; out of the millions of tiny tips that make up an array, only a tiny fraction actually emit electrons [93].

However, with breakthroughs in nano and micro-electromechanical technologies, a miniaturized cold cathode vacuum tube has successfully been produced. Carbon nanotube arrays are used as cathodes, and since they are naturally very narrow (10nm diameter), this makes them ideal field emitters as they can emit large current densities at low electric fields [94]. The miniature triode is shown below (figure 31).

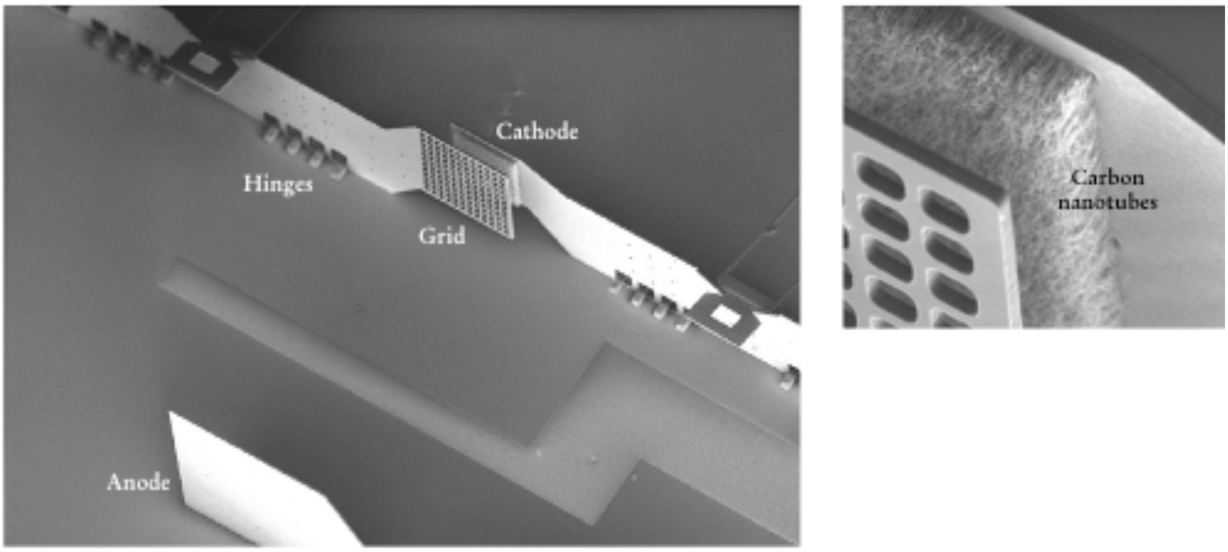

Figure 31: A miniaturized vacuum tube triode using carbon nanotubes as field emitters.
The distance between the anode and cathode is roughly 200um, the distance between the grid to cathode is 20um whilst the diameter of carbon nanotubes is 10nm, and length 8um [95]

The miniature triode exhibited much of the same voltage-current relationships as its larger predecessor (figure 32). However, only modest gains were achieved (in the region of 2 to 4 uS). Furthermore, like earlier cold cathode devices, only a fraction of the nanotubes were able to emit electrons and as a result the device was not able to deliver to its full potential. Whilst these facts clearly highlight that there is a long way to go before this technology will be used in commercial applications, many promising results were presented. These included a high efficiency (power outputted at the anode is almost 40 times greater than that intercepted by the grid [96]) and unlike spindt emitters carbon nanotubes have proven to be more robust to poor vacuums [97]. The modest success achieved importantly demonstrates that vacuum electronic devices can be shrunk down to a micro scale.

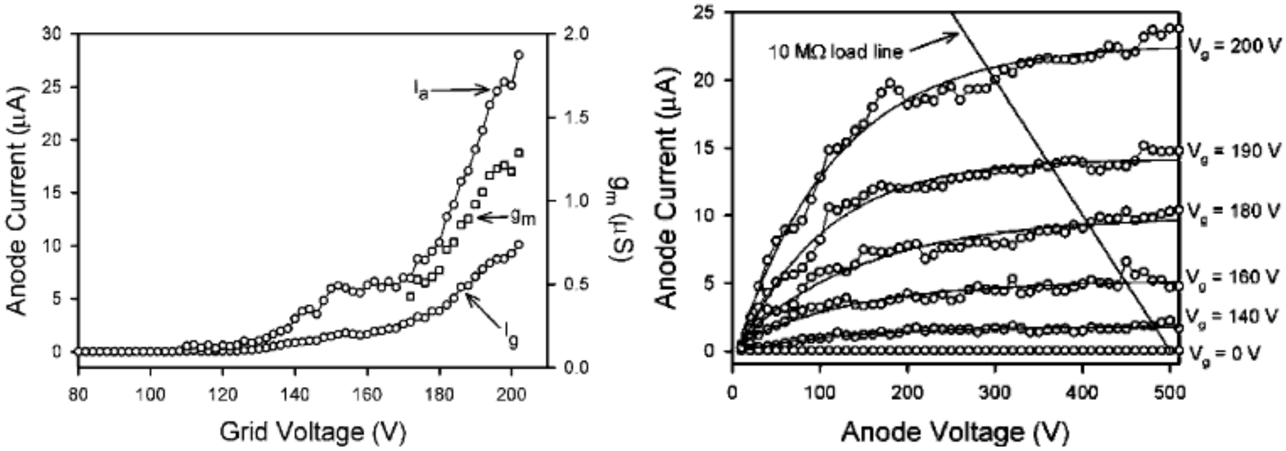

Figure 32: Graph on left shows the anode current, transconductance and grid current as a function of grid voltage for the mini-triode. The graph on the right shows the anode current as a function of anode voltage. [98]

In addition to its initial success, more recent findings have also helped overcome some of the miniature triodes limitations including getting more emitters to emit. It has been shown that the 'electrostatic screening effect' that the mini-triode suffered from could be countered by arranging the nanotube emitters in bundled arrays (figure 32). Through experiment an optimum arrangement has been discovered that allows larger current densities to be produced at the cathode [99]. These findings helped overcome some of the earlier deficiencies but problems still remain, such as nanotube emitters being dislodged at high fields due to poor adhesion to the substrate they are placed on [100].

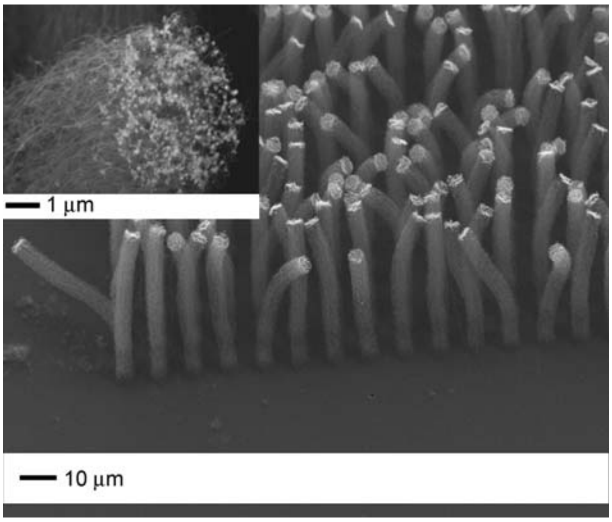

Figure 32: Bundles of carbon nanotubes arranged in arrays for optimum emission. Inset shows one bundle containing hundreds of nanotubes. [101]

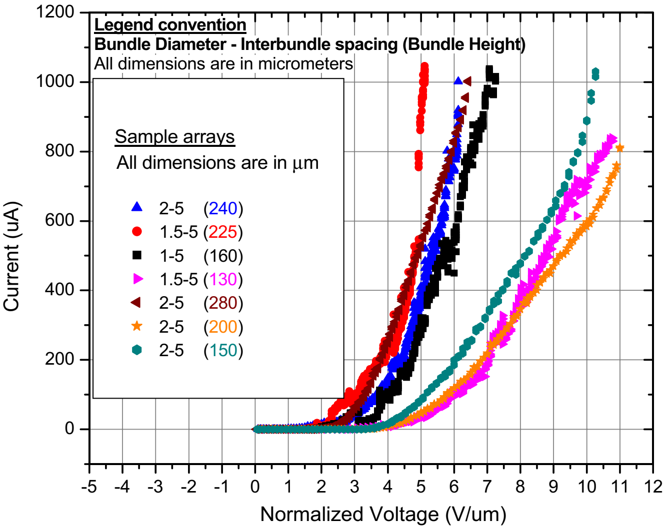

Figure 33: Graph illustrating the anode current as a function of grid voltage and its dependence on different bundle arrangements. [102]

Whilst this technology is still in its infancy and has a number of obstacles to overcome, it seems quite promising. This is highlighted by the continuing work being put in by researchers. In employing field emitters, tubes will no longer have to rely on large amounts of energy for heated emission. As a result, these tubes will potentially be able to overcome some of the limitations of their predecessors whilst acquiring some of the advantages of their solid-state competitors. In doing so they could potentially have new applications in wireless communication systems as well as operation in space [103]. However, it is important to make a distinction between these new tubes and their predecessors, the traditional tubes that employed thermionic emitters. They can obviously no longer be regarded as 'thermionic valves' as they no longer utilize thermionic emission, however, they still rely on many of the same principles and can be classified as vacuum tubes.

Conclusion

The debate about the future of the thermionic valve and whether its use has come to an end is still often discussed. According to our research, we think this is a very complicated question involving multiple points of views. Even within our group, opinions differed. Thus, it is impossible and irresponsible to give a yes or no judgment on the matter. Therefore, we decided to give a well-informed verdict that took into consideration all the findings of our research and show you a balanced perspective on the future of thermionic valves.

According to our research, in most areas, such as computing, solid-state devices have replaced valves. The range of their applications is extremely limited nowadays. From the present section, we have demonstrated that the valve still has superiorities over other technologies in certain domains. For example, in audio amplification, vacuum tubes are adored worldwide by music lovers for their aesthetic appeal and distinct sound signature. They also continue to play an irreplaceable role in high-power radio frequency amplifying or transmitting equipment. However, every widely-used product is chosen by many factors like efficiency and cost. Once some new technology can replace electron tubes and be economically superior, tubes are most likely to become obsolete. Although there is no guarantee that in the future there will be devices that can achieve better performance than vacuum tubes in these areas. It is also worth noting, that competing technologies have forced vacuum tube designers to improve their operational characteristics. Taking the steady rate of their improvement into consideration, tubes are still likely to fulfil the specialised functions they currently carry out. But even so, the chance for these applications to lessen is much larger than the chance to enhance. In other words, it is quite impossible for thermionic valves to be applied to any more new fields since technical development will never go back. Though enthusiasts, out of love and nostalgia, venture to repeat what their predecessors have done, it is unlikely there will be a second spring for the tube. In this sense, the future of thermionic valves is bleak because they will not have the opportunity to be developed for new applications.

Valves, despite making massive contributions throughout their history, still suffer from many of the same disadvantages they did a century ago. These include, among other things, large power consumption. In today's energy conscious world, traditional valves are therefore unlikely to find their way back into widespread commercial applications. However, besides the specialised functions they fulfil in medical and academic fields, new types of valves could play an important role in the future. Using new technologies such as carbon nanotubes and micro-electromechanical devices, new field emitter micro-valves can be produced. These, unlike their predecessors, do not rely on wasteful heating to operate. Consequently, they could lead to the expansion of vacuum tube devices in novel applications such as on-chip amplifiers and SED monitors.

However, it is important to acknowledge that it is very different from the traditional thermionic valves; it employs field rather than thermionic emitters. So despite it having the potential to perform as well as, or even better than competing technologies, the days of the traditional valves that employ thermionic emitters relying on wasteful heating are likely to disappear in the future. As a result, one can argue that traditional tubes, with the exception of certain specialised applications (in which they are more efficient than any competing technology) will be replaced, because they do not meet the energy requirements and the trend of low-carbon economy.

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Group Management

This section briefly covers the responsibilities and contributions each member made to this project. The nature of our project, which naturally split into three distinct sections, made the act of delegating tasks quite straightforward. The group was split into three pairs, with each pair tackling one time frame (the past, present or future of valves). The section each member was expected to work on is listed below, in addition to other responsibilities assigned to him or her.

Responsibilities:

Ekaterina Bayguzina: Responsible for developing the past section for both the report and website, more specifically the history and development of the vacuum tube.

Qinxin Liu: Responsible for developing the past section for both the report and website, more specifically operation of vacuum tubes and their early applications. In addition was assigned the role of vice captain (run meetings in the event of the group leader being absent).

Yunzhi Wang: Responsible for developing the present section for both the report and website. Focus would be placed on existing applications and how these devices worked. In addition, was assigned the role of treasurer and was hence responsible for the £50 allowance allocated to us.

Ngai-Han Liu: Responsible for assisting in developing the present section, main responsibility was setting up the website.

Ye Tian: Responsible for developing the future section, specifically the current applications that would continue to be used in the future.

Hamza Javed: Group leader, responsibilities included setting group meetings and deadlines. Also responsible for the future section of the report and website, with focus placed on novel future applications.

Contributions:

The section below contains statements from each member describing their contribution to the project. It is worth noting, that as a group, we felt all members contributed evenly.

Ekaterina Bayguzina:

I was responsible for developing the past section of the report and website, namely the history part. A lot of review articles, as well as original patents (e.g. Fleming's and de Forest's patents), and electronics history books were used in bringing together all the important events and facts. I also tried to explain the basic operating principles of early tubes, and how the characteristics of the tubes were gradually improved during the 1st half of the 20th century. I used the timeline structure and pictures of the inventions or inventors for the project website.

I also wrote the section about Klystron, which is related to the present section of our report. Finally, I contributed to compiling the whole report together, by formatting, proofreading and putting in order all the sections with figures and references.

Qinxin Liu:

My efforts included writing up the past section, where I mostly focussed on the operating principles of thermionic devices. In addition to this, I wrote the TWT section for the present section as well, where I concentrated on their performance compared to solid-state alternatives.

I also contributed to the contents of the website; early applications, theory of operation and TWTs.

Yunzhi Wang:

My contribution to the project included writing the section on present day applications of vacuum tubes. I wrote about magnetrons and cathode ray tubes. I explained the operating principles of these devices, as well as compared them with competing technologies where possible. In addition to my work on the report, I helped compile the different sections of the report together with Ye Tian and Ekaterina.

I also utilised the financial allowance we were provided by using it to print out our report.

Ngai-Han Liu:

My contribution included writing the section on present day applications of vacuum tubes. My section focused on alternative displays to CRTs, as well as sound and transmission methods using vacuum tubes. I also edited the present section and improved the standard of English (being a native speaker).

My main contribution was, however, in the form of the website. Where I designed and developed an original website template. This included pure CSS formatting and a Flash timeline as well as a navigation menu. I also arranged the content for the present section in the website.

Ye Tian:

For this project I was assigned to work on the future section of the report with our leader Hamza. My main contribution was to the X-ray tube and its possible future application. I also worked on the first draft of the final conclusion.

Besides the future section, I helped combine all the subsections from each subgroup into one report.

Hamza Javed:

As leader of the group, a lot of my contribution to the project was to manage and keep track of our work. I was fortunate enough to have a highly motivated and enthusiastic group of people to work with, and so was able to perform my job with relative ease.

In addition to managing the group, I contributed to the future section, focussing on the novel applications such as cold cathode vacuum tubes using field emitters and tubes in academic applications. I also assisted Ngai-Han in adding the content of the website (future section) and once the report had been put together, edited, formatted and proofread it until our final draft was produced.