The History and Modern Applications of the Vacuum Tube Transistor

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Abstract—This document aims to teach the reader about the history and modern applications of the vacuum tube transistor. This document will start by giving a brief recap of the behavior of a transistor. Next it will cover the first triode, tetrode, and pentode, then explore modern applications in audio, military, and high power and high frequency applications. Lastly, nanoscale vacuum tube transistor research will be covered to give a sense of what the future holds for the vacuum tube transistor.
The intended audience for this document is anyone who has basic analog circuit knowledge who is interested in learning about vacuum tube transistors. Most universities do not teach about vacuum tube transistors because they have become obsolete, so this document is targeted to most university engineering students.
The chosen style guide is the IEEE style guide. This style guide best suites my subject because it is an electrical engineering technical subject.

1 Introduction

When the tube transistor was originally invented in 1906 by Lee De, it was the only way to achieve a current/voltage controlled current type behavior. While the tube was the first transistor [3], it has since then been deprecated from most modern day applications. However, there are still some niche communities that still use tube transistors. The tube transistor remains dominant in the audiophile market because of the unique sound that the tube produces in audio amplifiers. Security reasons, such as stability under electromagnetic interference, make them more viable for government and military applications. There are also some high power applications that benefit from the properties of tube transistors.

2 Tube Transistor Behavior

It is important to understand how a tube transistor works conceptually before trying to understand the history of the tube transistor. This is because tube transistor has evolved to push the limits of the physical nature of the tube transistor. Tubes also evolved to fit specific needs which can be done by changing the characteristics of the tube transistor.

There are many variations on of a tube transistor, however the most basic tube transistor is the triode. The triode has three main connection points: the heating filament, the grid, and the plate. The heating filament is commonly referred to as the cathode and the plate is commonly referred to as the anode. In figure 1, the plate wraps around the grid which wraps around the heating filament. The important thing to note from this setup is that the grid is placed between the heating filament and the plate.

To use a triode tube transistor, one must put a charge on the heating filament by supplying it with a voltage. The goal is to get these charges to jump from the heating filament to the plate. This can be done by changing the charge on the grid. By doing so, the charges on the heating filament get attracted to the charges on the grid and end up jumping through the grid to the plate. This type of tube behavior is referred to as a thermionic valve.[2]

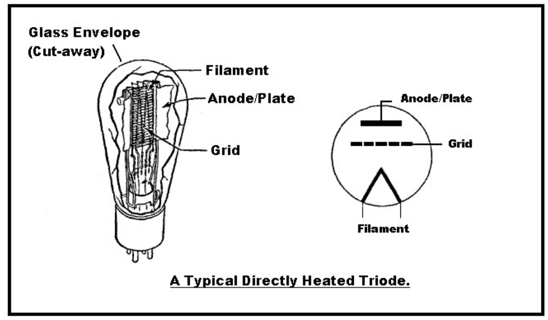

Fig. 1. On the left is a diagram showing the inside to a Vacuum Fluorescent Device (VFD) which is a tube transistor used as a display. The diagram shows the heating filament (labeled 'Filament'), the grid, and the plate (labeled 'Anode/Plate'). On the right is the equivalent circuit element symbol. [1]

This process is often tweaked by changing what fills the inside of the tube. Most tubes have vacuums to allow the charges to jump, however, some engineers have designed tubes to have gasses inside of the tubes. This effectively changes the characteristics of the tube.

3 History of the Tube Transistor

3.1 Triodes

3.1.1 1906: The First Triode "Audion"

You can thank Lee De Forest for the invention of the transistor. In 1906, Lee De, a physicists, used the published works on the first vacuum tube by Joseph John Thomson to invent the first vacuum tube triode transistor which Forest called the "audion" [4]. The Audion revolutionized electronics at the time as it made it possible to amplify electrical signals, such as audio from a radio, albeit only enough to hear from headphones and not from speakers.

The Audion is a triode and thus has a heating filament, a metal grid, and a plate. The tube was also filled with gas which is now realized to have been unnecessary and actually made the tube less linear, meaning that the current flowing from the heating filament to the plate as a function of voltage at the gate is less linear when tube is filled with the gas. Also, the gas inside the glass tube would leak which significantly lowered the lifespan of the tube. These

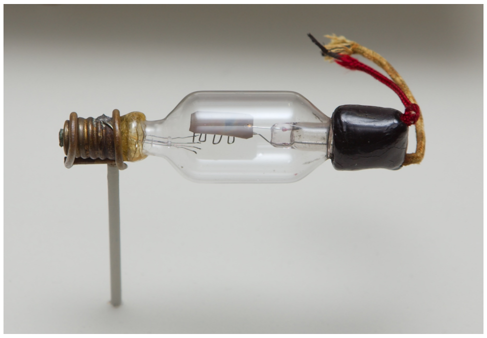

Fig. 2. Lee De Forest's Audion Tube. Notice the three connectors: one on the left and two on the right. These are for the heating filament, grid, and plate.

were among many flaws that the Audion had, and during this time, not enough was known about how the Audion worked to be able to create an engineering model that could explain the Audion's behavior.

3.1.2 1922: Super Radiotron Tube Transistor

In 1922, Irving Langmuir, a matallurgical engineer, created a triode vacuum tube that could output 20 Kilowatts of power. This allowed for audio to be amplified enough to be heard from speakers rather than just headphones. The super radiotron tube, unlike the audion tube, had less air inside the tube which meant that it was more of a vacuum inside the glass, thus extending the tube's lifespan and making the tube more linear. Another good feature of the radiotron tube was that is was significntly smaller than most other tubes, thus making it more viable for implimentation.[5]

Due to the improvements in power output, tubes were being produced for the sole purpose of transmitting radio waves. The super radiotron was capable of transmitting radio waves thousands of miles. [5]

3.1.3 1922: Bell Laboratories AT&T

Shortly after the super radiotron was released, Bell Laboratories came out with a tube called the AT&T tube that would be capable of outputting 100 Kilowatts [6]. These types of high power tubes had issues with overheating which Bell Laboratories solved these issues by water cooling and by sealing the metal of the tube to the glass of the tube which stopped air from leaking into the tube when under temperatures of up to 300C. [6] These advancements lead to the ability to reliably communicate over telephone.

3.2 Tetrodes and Pentodes

Triode tubes had issues when trying to operate at high-frequencies because of a phenomenon called the Miller Effect which states that there can sometimes be an increase in parasitic capacitance at the gate of the triode. This capacitance is caused by the gate and the plate being next to each other. Miller Effect effectively increases the amount of time it takes to change the voltage at the gate, which in turn limits the operating frequency of the tube.

3.2.1 1919: The First Tetrode

In 1919, a physicist named Walter H. Schotty invented what is known as a tetrode. The tetrode aimed to remove the issues caused by the Miller Effect by adding another grid called a screen grid. The other grid is renamed to be called the control grid in order to differentiate it from the screen grid.

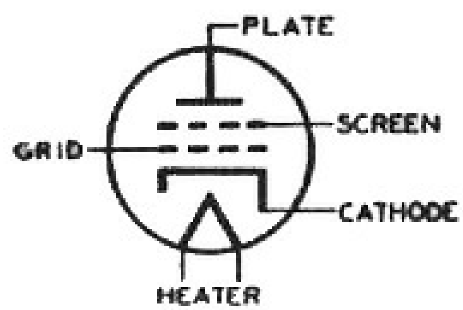

Fig. 3. Circuit element symbol for a tetrode tube transistor. Notice how there are now two grids: a screen grid and a control grid (labeled 'GRID'). The screen grid is placed in between the control grid and the plate. [7]

The tetrode still operates similarly to the triode, in that it still uses a thermionic valve and is still controlled by supplying a voltage to the control grid. However, the goal of the screen grid in the tetrode is to create a barrier between the grid and the plate that will not allow any capacitance to build on the grid. To do this the screen grid needs to be supplied with a voltage similar to the plate and needs to be bypassed to ground via a capacitor. This will take any charge that builds up on the grid, that would have otherwise caused a build in cpacitance, and send it to ground via the screen grid, thus eliminating the Miller Effect.

While the tetrode did fix the unwanted effects of the Miller Effect, it introduced another unwanted effect - a second anode. When electrons hit the plate, they can sometimes bounce. Since the new grid that the tetrode has is similar in voltage to the plate, the electrons that bounce off the plate can sometimes be captured and sent to ground via the screen. This reduces the maximum output current the tetrode can have, thus reducing the maximum power output. [2]

3.2.2 1926: The First Pentode

To fix the issue of the electrons bouncing back onto the screen in the tetrode, Bernard D. H. Tellegen invented the pentode in 1926. The pentode design adds another grid called the suppressor grid which goes between the plate and the screen grid.

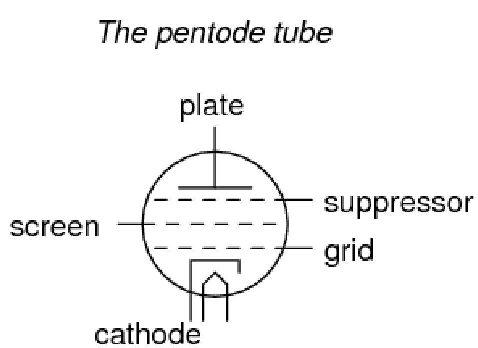

Fig. 4. Circuit element symbol for a pentode tube transistor. There is a plate, a heating filament (labeled 'cathode'), a control grid (labeled 'grid'), a screen grid (labeled 'screen'), and a supressor grid (leabled 'supressor'). [8]

The goal of the suppressor grid is to mimic a cathode (the heating filament) in order to make sure that the electrons that bounce back when hitting the plate do not get captured by the screen grid. By making the suppressor grid have a negative charge (same as cathode), the electrons that bounce off the plate will want to repel away from the suppressor grid and back onto the plate. [2]

4 Modern Applications

Since the invention of nanoscale solid state transistors, the vacuum tube is no longer used in most applications. Some of the remaining modern applications of vacuum tube transistors include Audiophile equipment, use in the military, and high power and high frequency applications.

4.1 Audiophile

Audiophile is a term used to describe a person who is obsessed with sound reproduction. One of the main components of sound reproduction is the audio amplifier. There are many types of audio amplifiers, however all audio amplifiers use transistors. Depending on the characteristics of the transistor, different sound characteristics can be achieved.

4.1.1 The Tube Sound

The reason why vacuum tube transistors are still commonly used in audio amplifiers is because they produce what is known as "the tube sound". There is a huge debate in the audiophile community over whether or not the tube sound is better or worse than the sound produced from solid state transistor amplifiers. Some think that the tube sound sounds more musical and smooth sounding compared the accurate and artificial sound from solid state amplifiers.

The factors that make tube transistors have the tube sound include input/output impedance, bandwidth, and clipping/distortion. While these are factors that make up the tube sound, the tube sound can also vary depending on the type of tube used (triode vs. tetrode vs. pentode) and how it is used (amplifier topologies, power supplies, etc).

In a voltage audio amplifier, the desired input impedance is infinity. This is to make sure that the amplifier will not draw any current from the source which would alter the signal being amplified. Tube amplifiers tend to have much higher input impedance than solid state amplifiers [9] . The output impedance of a voltage audio amplifier ideally should be zero ohms which can cause an issue with tube amplifiers since tube amplifiers tend to have higher output impedance. This means that as far as output impedance goes, solid state amplifiers are technically better than tube amplifiers.

Tube amplifiers tend to have a more narrow bandwidth than solid state amplifiers because of the circuit topologies that are used. The output impedance and the decoupling capacitance will give the amplifier a high pass filter effect. In guitar amplifiers, a low pass filter effect comes from the high input impedance from the amplifier and the high input capacitance of long guitar cables.

The largest factor that goes into making the tube sound is the clipping characteristics of vacuum tube transistors. In an audio amplifier, clipping occurs when the signal driving the amplifier has a high enough voltage that when the amplifier outputs the amplified signal, the voltage is too much for the amplifier to output. When overdriving an amplifier like this, the transistor is put into saturation. When vacuum tube transistors saturated, the harmonic distortion is only even order, whereas in solid state transistors, the harmonic distortion in saturation is of both even and odd order. This results in what is known as ”soft clipping”. This characteristic of the tube transistor is the main reason why they are so popular in guitar amplifiers where clipping and distortion are desired effects.

A transistor that is more linear, meaning that as the input and output voltages have a linear relationship, is more ideal for an amplifier. In a solid state amplifier, linearity is achieved by adding in negative feedback. Tube amplifiers have issues when using negative feedback because it can introduce phase shifts in the output. However, without negative feedback, the total harmonic distortion in the upper frequency range can increase. Despite this, the need for negative feedback in a tube amplifier is less than in a solid state amplifier because tube transistors tend to be more linear than solid state transistors with minimal negative feedback. This is especially the case in triode tubes.

4.2 High Power and High Frequency Applications

While not all of these applications involve transistors, they involve vacuum tubes.

4.2.1 Cavity Magnetron: Microwaves

The vacuum tube called the Cavity Magnetron, invented in 1910 by H. Gerdien, can be found in all microwave ovens. The magnetron tube is capable of producing microwaves by using a magnetic field to excite electrons that move past small vacuum pockets. These vacuum pockets, known as cavity resonators, allow the electrons to resonate inside the cavities at high frequency microwaves.

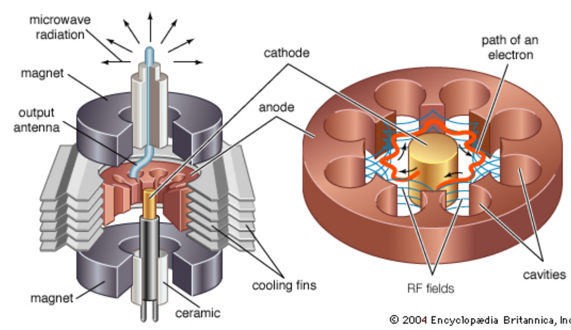

Fig. 5. This schematic diagram of the Cavity Magnetron shows the anode, cathode, the magnets that supply the magnetic field, the vacuum cavities, and the path the electrons will take once excited. Notice how the electron path is in an ocselating fashion and how this vacuum tube does not contain any type of control grid. [12]

The magnetron has a waveguide which can emit the microwaves. In microwave ovens, the magnetron's waveguide emits the microwaves into the area where the food goes to cook.

4.2.2 Klystron: Particle Accelerators and Satellites

The main issue with the Cavity Magnetron is that it does not have any amplification properties, thus making it only able to source relatively low power microwaves. Some applications such as particle accelerators and satellites need high power and thus cannot use the magnetron on its own. In 1937, the Klystron was invented by Russell and Sigurd Varian. The klystron is capable of amplifing microwaves into the tens of megawatts [13].

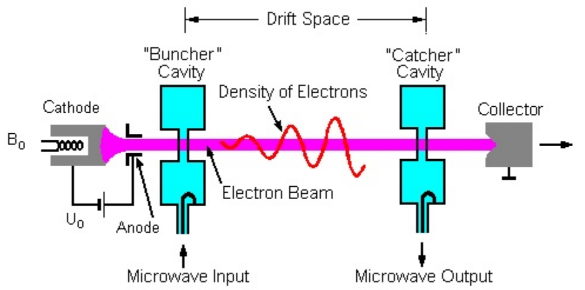

Fig. 6. This schematic diagram of the Klystron shows the thermionic cathode, the anode which is used in this case to direct the electrons into a beam, the buncher which is used as an input, the catcher which is used as the output, and the collector. [12]

The klystron works by having a heated filament supply electrons which then get attracted to the anode. The anode is arranged so that the electrons get focused into a beam. To keep the beam together, a magnetic field is applied along the beam. The beam goes through the buncher cavity where the input signal gets picked up on the beam. This happens because when the beam goes through the buncher cavity, it is actually passing through oscillating grids which transfer the oscillation to the beam when the beam passes through them. This causes some of the electrons on the beam to have modulating velocity - some will move slower and some will move faster. As the beam travels to the catcher cavity, the electrons that are moving slowly and the electrons that are moving fast will bunch up into dense bunches of slow and fast moving electrons, thus creating an amplification effect. The catcher can then pick up the amplified signal which can be used as the output of the vacuum tube.

The klystron is used in many different types of applications such as particle accelerators, satellite and radar communication, and radiation oncology. The klystron is used in the Storage Ring, a circular particle accelerator, at the Australian Synchrotron. The klystron's purpose is to maintain the energy of the particle accelerator beam. It is also used in the SLAC National Accelerator Laboratory where it is being used in the largest particle accelerator in the world. The accelerator is two miles long and the building that holds the klystron is the longest building in the United States. In the SLAC particle accelerator, the klystron outputs around 50MW pulses at 2856MHz. Besides particle accelerators, the klystron is used as transmitters that transmit up to 1MW of continuous power at 2380MHz in the Arecibo Planetary Radar Observatory. These trasmitted signals go out into space and reflect back, at which point they can be recieved and rendered into images of astroids, planets, etc. [13]

4.2.3 Traveling-Wave Tube: High Frequency RF Communication

Similarly to the klystron, the Traveling-Wave Tube (TWT) is used to amplify signals that are in the range of microwaves.

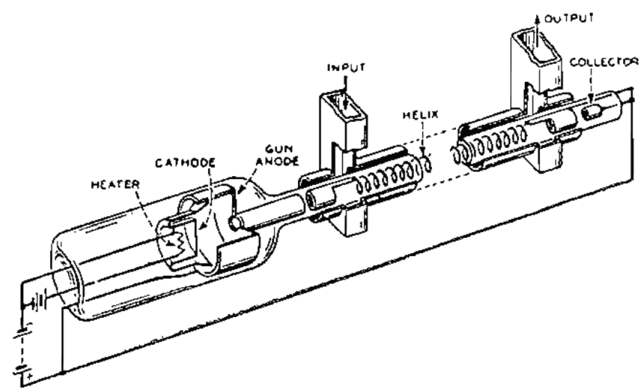

Fig. 7. This diagram shows the traveling-wave tube. There is a thermionic cathode, an anode that causes the electrons to shoot into a beam, an input and output similar to that of the klystron, a collector to collect the electrons once they have reached the end, and the helix which creates an oscillating magnetic field. [14]

The difference between the klystron and the TWT is that rather than creating the velocity modulation in the beam from passing the beam through a grid, the TWT has a helix, a copper coil, that will carry the input signal. This coil will produce an oscillating magnetic field at the same frequency as the input signal. This magnetic field will produce positive and negative potential across the beam which is what will cause the velocity modulation. In some applications, a control grid is necessary to allow the TWT to pulse. The control grid would go after the anode gun.

The reason to use a TWT over a klystron comes down to bandwidth, gain, and size. The

TWT can achieve a bandwidth of up to a full octave, whereas the klystron is much narrower. The klystron still dominates in terms of gain since the TWT can only amplify up to about 40dB. The TWT is only about one foot long, whereas the klystron can be as large as a person.

TABLE I

GLOBAL SELECTION OF CURRENT HELIX AND COUPLED CAVITY TWTs

Market	Product	Manufacturer	Frequency/ Band (GHz)	Output Power (W)
Satellite Comms (Ground)	TH3977[5]	THALES	Ku	750
	VTU-6397H1[6]	CPI	Ku	1200 (Peak)/ 600 (CW)
	MTC5338X[7]	TELEDYNE MEC	C/X/Ku	350/600/350
	LD7314[8]	NEC	Ka	350 (Peak)/ 250 (CW)
Satellite Comms (Space)	9100HR[9]	L-3	K	50 to 130
	TH4725B[5]	THALES	Ku	100 to150
	TH4626[5]	THALES	Ka	30 to 60
Radar	VTS5754F[6]	CPI	S Duty	130K, 8%
	N10570A[10]	e2v	X	20K, 8% Duty
	TL35038[5]	THALES	Ka	1K, 12% Duty
ECM/EW	L6049[11]	L-3	4.5 to 18	110
	N20160[10]	e2v	4.5 to 18	50
	TH3893[5]	THALES	6 to 16	1500

Fig. 8. Table showing the types of applications and their associated TWT devices. [15]

The TWT is used mainly in RF communication whether that be in satellite communication, radar, or electronic countermeasure (ECM).

4.3 Military

While tube transistors are old technology, there are a few reasons why the military still use them. First, tube transistors are affected less by electromagnetic fields (EMF), radiation, and high temperatures, making them a more secure option over a solid state transistor for some environments. Second, they might be hard to replace in a system that already has them implemented and thus were never replaced.

In a vacuum tube, the electrons are traveling in a vacuum when jumping from the cathode to anode. Due to this, environmental effects that do not exist in vacuums such as radiation, emf, and temperature will not affect the functionality of the vacuum tube transistor. This makes it more reliable for use in military applications such as nuclear warheads and radar.

In 2008 there was a proposed plan called the Reliable Replacement Warhead Program (RRW) to replace outdated equipment in nuclear warheads. This sparked a debate on whether or not this would included the vacuum tubes that were being used in the radar fuses which tell the warhead when it has reached an altitude where it should detonate. These vacuum tubes have remained due to the fact that "Since implementing a moratorium on nuclear testing in 1992, the United States has opted to extend the life of existing warheads while minimizing deviations from the original specifications." [10] While these vacuum tubes could be easily replaced, The National Nuclear Security Administration have repelled any requests to do so simply because it would risk the lifespan of the warheads.

5 THE FUTURE: NANOSCALE VACUUM TUBE TRANSISTOR RESEARCH

The main reasons why there are not many vacuum tube transistors used in modern electronics is because of how big they are and how much power it takes to operate them. Most modern electronics use solid state transistors which are on the scale of nanometers, allowing them to be more densely integrated into a system. The figure below can give a sense of why vacuum tube transistors are not practical for use in modern technology.

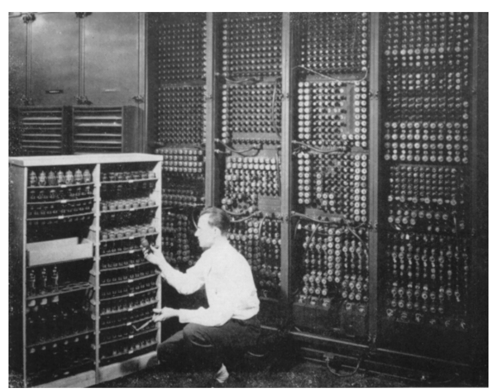

Fig. 9. The ENIAC was a computer that functioned as a calculator. It took up a 20ft by 40ft room and weighed 30 tons. The computer contained more than 18,000 vacuum tubes. In this image, a man is trying to replace a broken tube. [16]

In this design, the emitter is similar to the heating filament in a vacuum tube transistor in that it will hold the electrons before they jump to the collector which is similar to the plate. The gate is similar to the grid since it will either allow or block the electrons at the emitter from jumping to the collector. The main difference in this design from the standard triode design is that the emitter does not need to be heated like in the triode. Instead it is connected to a source, similar to a standard solid state transistor.

If vacuum tube transistors could be made on a nanometer scale, the advantages of vacuum tube transistors could be utilized in a practical sense. These advantage not only include the ability to be used in extreme environments but also operate at much higher frequencies than a typical solid state transistor. This is important for the future of technology because the solid state transistor technology is starting to hit its limits as far as speed and density. The silicon layers in a solid state transistor need to be at least five atoms thick in order to operate[18]. These physical limits, once reached, will render Moore's Law obsolete, and thus a new transistor needs to be invented in order to replace the limited solid state transistor.

NASA has taken up the challenge and has developed a nanoscale vacuum tube transistor that they call the Vacuum Channel Transistor (VCT). This transistor is essentially a triode vacuum tube transistor, meaning that it has a cathode (emitter), a gate, and an anode (collector). The VCT is fabricated using silicon layers which have a small gap between the emitter and collector. According to NASA, the size of this gap is small enough (10nm) that having a vacuum is not needed [17]. This means that the gap can be filled with a gas while still achieving a vacuum-like effect.

Since the distance that the electrons have to travel from the cathode to the anode is on the scale of nanometers and the fact that the electrons in a vacuum move faster than electrons in silicon, the VCT can operate orders of magnitude faster than a solid state transistor. The VCT also has a lower turn-on voltage than solid state transistors.

Some applications of this technology include the use in nanophotonics and biomedical technology. Nanophotonics would require operating speeds in the range of Terahertz and biomedical technology can require speeds in range of Exahertz [18]. VCTs could theoretically replace the solid state transistor, thus increasing the speed of technology such as computers, phones, etc. The VCT could be the future building block for all technology.

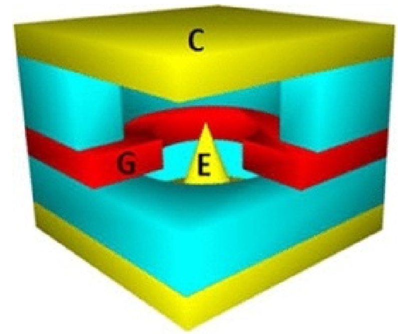

Fig. 10. Structure of the VCT. There is the emitter (E), gate (G), and collector (C).

6 Conclusion

The vacuum tube transistor started out as the Audion, a tube that could hardly output about 10W of power. Now, there are vacuum tubes that can output microwaves in the range of megawatts. Despite the bumps in the vacuum tube's evolution, the tube continues to evolve with NASA's vacuum channel transistor research. Will the vacuum tube ever return to mainstream electronics or will it continue to be only used in niche applications?

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