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Electronic valve instabilities and Mode jumps

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Abstract: This article reviews the invention of the electronic valve (lightbulb, audion, diode, triode and magnetron) and their modern counterpart (diode sputter ion pump and the diode parallel-plate RIE reactor), in the period from the 1870's to the 2016. Emphasis is given to the human nature of discovery, invention and patent filing and litigation, along with the fundamental physics and electrical engineering concepts applied within the inventions. The malfunction (mode jumps and instabilities) of the electronic valves are examined using an electrical engineering approach. In the absent of such an approach for the diode sputter ion pump "Argon instability", coupled ordinary differential equations have been used to the mimic the dynamics of the heterogeneous gas burial / release process. Lastly, heterogeneous chemical mode jumps in the metal-organic reactive etch process of GaAs semiconductor material has also been considered.

Keywords: Space-charge, electronic valves, sputter ion pump, RIE reactor, modes, instabilities.

1. Introduction

The fourth state of matter (plasma) has had an enormous effect on enhancing our everyday lives. Examples include: the use of plasma etching and deposition for the fabrication of electrical circuits used within cell-phones and laptops; modern aeroplanes that are adhesively bonded together with the help of plasma, or glow discharge, that is contained within an electronic valve. Plasmas also play a significant role in the deposition of barrier layers for packaging that prolongs foods shelve life.

The aim of this work is to review the development of plasma processing from its origins starting with its use in the electric lightbulb and its progression in design to the sputter ion pump and the diode reactive ion etching (RIE) plasma reactor. This paper is an attempt to thread together some 150 years of our understanding of space-charge and plasma processing malfunction, where the malfunction arises from mode change or instability due to gas impurities, the internal electromagnetic (***ExB***) field or the applied external circuity.

The writing of this paper has been approached in a qualitative manner so that people outside the word of plasma processing may appreciate the human nature of discovery, invention and patent litigation. Moreover it is hoped that this

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approach will influence people involved in chaos theory, and take up some of concepts for further research. Where possible examples of the original published work are cited in order to provide a clear chronological sequence of events, but the secrets of two world wars prevented the text of some of the most valuable documents being written until sometime later. The development of vacuum production and measurement is inextricably linked to the electron valve and plasma processing, therefore we recommend to the reader two articles that have find most helpful. These are: *Early applications of vacuum, from Aristotle to Langmuir* [1], and for plasma processing; *Glow discharges processes: sputtering and plasma etching* [2].

The challenge in writing such an article is the word conventions and units of measure that change with time and place. For example; in North America the phrase "electron tube" is used whereas in Britain "electron valve" is used. The unit of pressure also changed with time. The pressure unit of Torr is used in this work, purely for the reason that the majority of papers cited use this unit of measure. Finally it is worth recalling that a typical sputter deposition rate is one monolayer per second at a pressure of 1 x10^{-6} Torr [2].

2. Space-charge gas-phase historical perspective

2.1 Edison effect

This background is a review the applications of space-charge beginning with Thomas A. Edison's 1879 British patent of the incandescent electric lightbulb [3]. This patent actually infringed on an 1880 British patent by Joseph W. Swan [4]. This was because Swan had demonstrated his partially evacuated lightbulb at a lecture in Newcastle upon Tyne on December 18th 1878, where the lecture attached attention of the world, including Edison. Swan subsequently sued Edison in the British courts for patent infringement and won. As part of the settlement, the courts made Swan a partner in Edison's electric company in 1883. The jointly owned company become the Edison and Swan Electric Light Company of London-UK. During this period (1879), John Ambrose Fleming became the scientific adviser to the Edison Telephone Co. of London [5] and three years later, in 1880, was appointed "Electrician" to the Edison Electric Light Co. of London [5]. Such prodigious appointments gave Fleming a unique and detailed knowledge of how to manufacture a working lightbulb.

The basic principle of the incandescent electric lightbulb is that an evacuated glass bulb containing a filament is held between two electrodes and when electrical current is passed through the bulb's filament, the filament heats up and glows to an incandesce luminosity.

Both Edison and Swan used the hand operated Hermann Sprengel's mercury drop-pump to evacuate their lightbulbs to reach vacuum pressure of one millionth of an atmosphere. The difference between the lightbulbs; is that Swan used a carbonized paper filament and only a partially evacuated bulb: the poor quality of the vacuum caused the carbon to disintegrate rapidly, so the bulb glowed for just 13-and-a-half hours. After Edison and his assistants had tested thousands of materials, carbonized filament bamboo was found to last up to 1,200 hours. Today's incandescent bulbs are made of tungsten and last about 1,500 hours.

As we know the electric lightbulb changed our world through the phenomenon of the "Edison effect". This effect first observed in Edison's Menlo Park laboratory in 1879 by William J Hammer, while testing lightbulbs. Hammer, noticed a blue glow around the positive electrode within the evacuated bulb and a blackening of the wire and bulb at the negative electrode. It appeared that carbon was flying across the vacuum, and onto the walls of the bulb. He originally called this phenomenon the "Hammer's phantom shadow". In order to measure the current flow the lightbulb was fitted with a third electrode, that was connected a galvanometer and then back to the battery. When the galvanometer was connected to the positive terminal of the battery and the filament heated a current of a few milliamps was observed to flow, and no current flowed when connected to the negative terminal of the battery. See figure 1. From this experiment it was erroneously reasoned tha the carbon was also charged. This observation was filed as a patent by Edison in 1883 in America (*Electrical inductor*. U.S 307,301) and has become known as the "Edison effect" although at the time Edison did not know what was causing the effect. He did however put the device to practical use as a relay in electrical power stations [6], but never for wireless telegraphy.

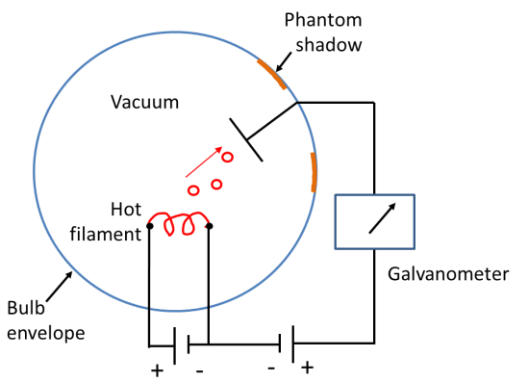

Figure 1. Schematic of "Hammer's phantom shadow" observation and the "Edison effect" measurement.

Hammer's phantom has become what we understand today as sputtering (spluttering without the letter l) that was first recorded by William R. Grove [7]. One should not feel to dishearten for Hammer as he built a central station in London to power 3,000 incandescent lamps on the Holborn Viaduct and invented the electric advertising sign. It is also worth noting that the British chemists Frederick Guthrie was the first to reported the phenomenon of thermionic emission in 1873 [8] and then went on to mentor a young John Ambrose Fleming.

Some 15 years later in a series of experiments designed to study the nature of electric discharge in a high-vacuum cathode-ray tube, the British physicist Joseph J. Thomson discovered the electron [9] which was causing the Hammer's phantom shadow. We now call this effect "Thermionic emission" where electrons are emitted from a heated electrode and travel to the cold electrode. The understanding of this emission has become the basis of the electron valve theory.

2.2 Thermionic diode

In 1885 Fleming was appointed to the newly-created Professorship of Electrical Engineering at University College in Gower Street, London. Subsequently, he was appointed, in 1899, as associated scientific adviser to the Marconi Company with the specific task of designing and building the power plant and telegraphy equipment for the Poldhu wireless station [10]: which became the site of the first successful transatlantic signal transmission in December 1901. Through these experiences Fleming came upon the idea that that the "Edison effect" could be used to rectify (demodulate) very high frequency alternating currents. His idea reveals an aspect of the creative process in which an idea is taken out of its original contexts and is used for another purpose. Sungook Hong [11] has suggested that Fleming may have been influenced by Nodon's electrolytic rectifier operating in the frequency of 42-84 Hz [12]. Indeed Fleming wrote in his 1904 paper (On the conversion of electric oscillations in to continuous currents by means of a vacuum valve [13]):

> *"This action has been studied and is basis of many technical devices such as the Nodon electric valve. The electrochemical action by which this unilateral conductivity is produced involves, however, a time element, and after much experimenting I found that it did not operate with high frequency currents".*

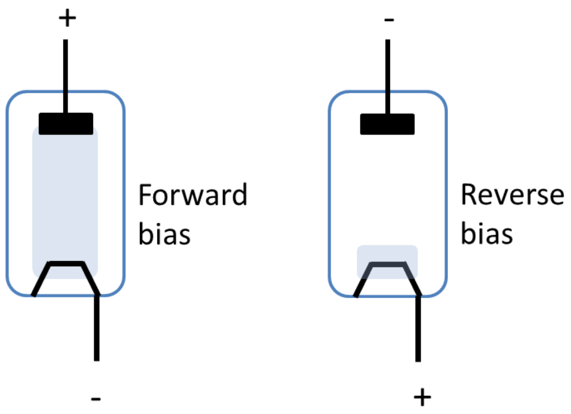

Figure 2. Diode thermionic valve: a) forward bias and, b) reverse bias. Note that the heater is working, and the cathode is heated to incandescence in a high vacuum. The space-charge cloud is shown in blue.

The algebraic expressions of the Child-Langmuir Law that describes how current tends to vary with the applied voltage is given as:

$$I_a = \alpha(V_a)^{3/2} \qquad \text{Forward bias} \tag{1}$$

$$I_a = 0 \qquad \text{Reverse bias} \tag{2}$$

Where: I_a is the anode-cathode current, V_a is the potential difference between anode and cathode and α is a factor whose value depends on the size and shape of the anode and cathode, and inversely as the square of distance between the two electrodes.

The factor α plays an important role in the behaviour of the electronic valve performance, it is discussed further when the size and shape of electrodes, for a fixed inter electrode distance, is considered (*4.3 Diode parallel-plate RIE reactor*).

2.3 Triode

In 1905 the American electrical engineer Lee De Forest's experimented on and modified Ambrose Fleming's thermionic valve (subsequently owned by Guglielmo Marconi) and applied for a patent for his audion tube 1906 [14]. De Forest used the Heinrich Geissler's mercury displacement pump, which left behind a partial vacuum. The valve contained three electrodes; anode (plate or wing: word conventions of the era), grid and a cathode. In the Initial design the grid was placed outside the tube glass envelope, but later designs placed the control grid within the tube between the anode and cathode. This arrangement not only rectified the detected electrical signal, but also amplified the rectified single, thus making a new receiver for wireless telegraphy. Due to residual gas within the soft vacuum, the tube had many unpredictable amplitude modulation problems and only becoming a practical device after many development stages by other electricians and engineers. De Forest believed the residual gas was essential to its operation and maybe perhaps that is why he contracted the Latin verb "*aud*" (derived from the verb to mean hear) and the Greek noun "*ion*" to create the word audion to describe his tube. Nevertheless the audion tube eventually becomes known as the triode vacuum tube (valve).

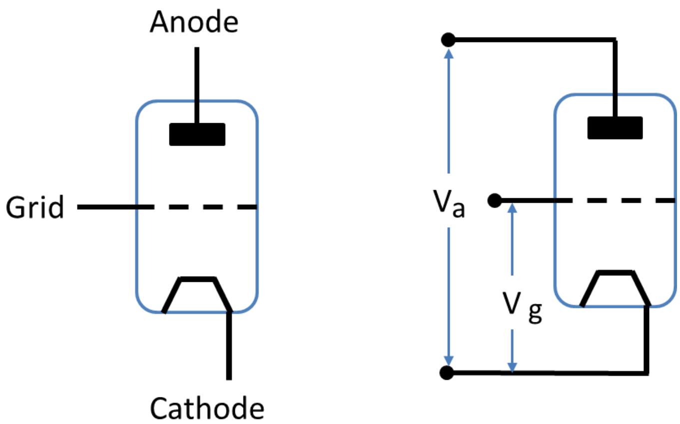

Figure 3. Triode; a) schematic of the triode valve and, b) triode voltage separation between the electrodes.

Under high vacuum conditions the two potential differences may be considered as: V_a potential difference between anode and cathode and, V_g the potential difference between grid and cathode. A modified version of the Child-Langmuir Law equation is used to estimate the anode-cathode current as:

$$I_a = \alpha(\mu V_g + V_a)^{3/2} \quad \text{Forward bias} \tag{3}$$

$$I_a = 0 \quad \text{Reverse bias} \tag{4}$$

In the case of Forward bias; $(\mu V_g + V_a) > 0$. The value μ is called the valve's amplification factor. In practice, real triodes (grid inside the vacuum bulb and close to the cathode) tend to have amplification factor value somewhere in the range 10-100.

Harold D Arnold (AT&T's Western Electric research branch) was one of the first people to recognize the significance of De Forest's audion tube as a way to amplify telephone signals and saw how the valve problems could be overcome [15]. By 1914 the audion tube was evacuated to a high vacuum standard of ~10^{-7} Torr using Gaede's rotary mercury pump thus allowing the valves modulation stage to work properly and was renamed the "kenotron" from the Greek word *keno* (empty, as in a vacuum) and *tron* (device, instrument, or a chamber where something happens).

At AT&T in early 1913 Edwin H. Armstrong demonstrated two external circuit methods to increase the amplification factor of the De Forest's audion tube [16]. This form of signal reinforcement, or regeneration, using external circuit elements (inductors and capacitors) is known today as positive-feedback.

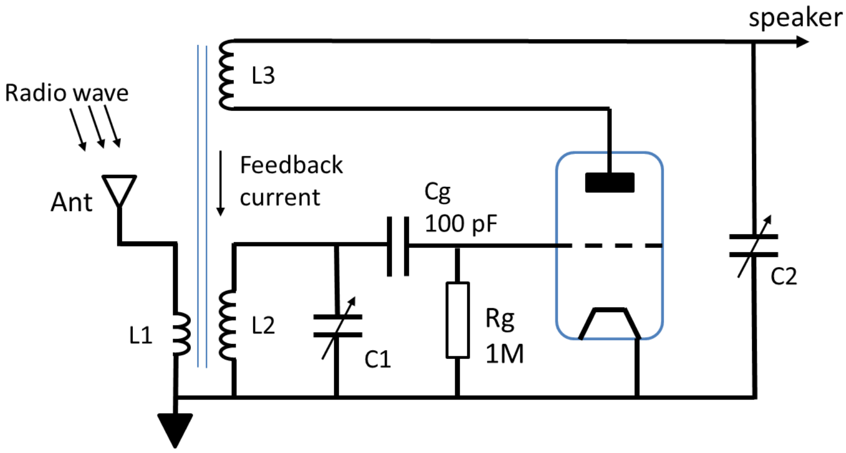

Figure 4. The basic Armstrong regenerative receiver circuit.

Figure 4 shows the basic Armstrong triode receiver circuit, comprising; the triode and; external inductor, capacitor and resistor (LCR) circuit components. With reference to this circuit, intercepted radio waves induce a voltage on the antenna that in-turn induced current flow through L1, which magnetically couples the RF energy to the L2-C1 tuned circuit. The grid circuit elements, *Cg* =100 pF and *Rg* = 1M Ohm couple the tuned radio signal to the triode's input. Amplified RF currents then flow in the anode circuit, setting up a magnetic field around L3 which mutually couples energy back into the input stage of the grid in phase with that imposed by the radio wave. Now the feedback of the in-phase signal amplifies the original signal, that is to say; the original signal is reinforced. If enough energy is fed back into grid input (by adjusting the C2 capacitor) sufficient amplification will cause the triode to break into oscillation, thus creating the possibility of the continuous-wave radio transmitter. Hence maximum amplification of the incoming radio signal occurs when the circuit is in the threshold of oscillation.

Armstrong's extensive investigation on the subject of positive-feedback was the issue of a ruinous litigation pursued by De Forest and Armstrong until 1934, when the US Supreme Court finally ruled that De Forest was the patent-owner. This dispute dragged on however until the final publication between the two parties was published in the Proceedings of IEEE, April 1997 [17] where the editor had the final say.

> ***Robert H. Marriott:*** *It has been frequently charged that there has been a lack of research in radio engineering carried out in physical research laboratories. Mr. Armstrong deserves much praise in carrying out this highly interesting investigation, and it is to be hoped that further valuable results will be obtained under similar auspices.*
>
> *This discussion is herewith closed.—Editor.*

The question of why a high vacuum is required to operate the audion tube was considered by Armstrong [16, 17], but no satisfactory answer was uncovered. The answer to this question however came from the physics community. Clement D. Child established that positively charged CaO ions experience mutual repulsion or a 'space-charge effect' as they travelled from a heated electrode to the cold electrode [18]. In his experiments the Sprengel and Toepler mercury diffusion pumps in combination with traps and bake-out procedures that could obtain the necessary high-vacuum was used. Under such high vacuum conditions the Child Law states [18]:

> *The space-charge limited current (SCLC) in a plane-parallel vacuum diode varies directly as the three-halve power of the anode voltage and inversely as the square of the distance separating the cathode and the anode.*

The application to electrons and curved electrodes was made by Irving Langmuir later in 1913 [19] and now both scientist are given credit in the space-charge limited current Law. Langmuir's diode experiments also revealed that molecular gas impurities (N_2, O_2, H_2O and CO), when ionised or dissociated caused a reduction in the current flow. Whereas argon gas induced an increase in current beyond the three-halve power Law as the space-charge was eliminated. To understand the reduction in current flow it is helpful to consider the first 4 constituent atomic and molecular gases, by volume, that makeup air at atmospheric pressure. Namely: N_2(78%), O_2(21%), Ar(0.933%), CO_2(0.003%) plus water vapour and other molecules. When the atoms and molecules undergo electron impact many different electron loss pathways may occur that untimely leads to a fall in the electron current. This may be interpreted by the following representative balanced gas-phase electron impact equation pathways: excitation ($e^- + N_2 = N_2^*$), attachment dissociation ($e^- + O_2 = O + O^-$) and (8) and, ionization ($e^- + Ar = 2e^- + Ar$). An inspection of these 4 reactions pathways, reveal all but one (ionization) involves the loss of an electron and is associated with a fall in current flow. In the case of argon gas ionization positive charged argon ions (Ar^+) are produced, and as observed by Langmuir sputtering of the heated filament occurs leading to a loss of material that became deposited on the bulb in the form of black bands, principally behind the anode. Although these limited pathways are single-step in nature, and no doubt give a partial picture, the reaction pathways provided a means of understanding the root cause of the erratic behaviour of the audion tube.

Langmuir further investigated filament evaporation reactions with nitrogen and oxygen. In the case tungsten that evaporates from the filament in a nitrogen environment the unstable compound WN_2 above 2400 K is formed, however, being unstable the compound does not remain on the surface, but either decomposes or volatilizes. A similar effect was also observed for platinum filaments in a low pressure oxygen environment due to the formation of PtO_2 [19]. The net effect of both reactions is to reduce the space-charge current.

Serendipity also plays a part in valve development. It happened when the Frenchman Paul Pichon happened to deliver the audion and kenotron tubes to the Marconi Company in London and not to the Telefunken Company of Germany at the outbreak of First World War [20]. Pichon had previously deserted the French Army in 1900 and immigrated to Germany, where he found employment as a technical representative for Telefunken Company. In this employment he visited USA to collect samples of wireless equipment from various companies and was on route back to Germany via London when war broke out. He requested the help of the Marconi Company in London who arranged a safe passage for him to France, in return however they kept the tube samples and their associated documentation. From this point in 1916 tubes produced in England were known as the R valve, while those in France were known as the TM triode.

2.4 Appleton and Van der Pol collaboration

When Edward V. Appleton began working at the Cavendish laboratory at the University of Cambridge he published work on the triode: *Note on the production of continuous electrical oscillations by the three-electrode valve*. [21]. The article was followed quickly afterwards in 1919 by a quantitative description of high-resistance leakage (conductance) between grid and filament during one halve of the grid voltage cycle and hence across the grid capacitor that produces amplification and oscillation [22]. These publications came to the notice of the young Balthasar Van der Pol who was working at the time at the Physical Laboratory of Teyler's Institute in Haarlem. The scientist formed a kindred spirt through their mutual interest in triode oscillations and quickly formed a working partnership. In 1921 their collaboration resulted in an R-type triode oscillograph study, that illustrated the current and voltage waveform at low frequency (16 Hz) departs from LCR lumped component theory to one that involved thermal cooling of the filament in one part of the grid voltage cycle [23].

This was followed in 1922 by the experimental and quantitative study of oscillation-hysteresis between two stable amplitude states [24]. Their work used a non-liner Maclaurin power series expansion, where the first three odd terms (0, 3, and 5) are used, to fit the measured grid voltage data. With an additional two odd terms (7 and 9) to fit grid voltage data that neither approach zero. A description of the Maclaurin power series expansion used to examine plasma non-linearity can be found in reference [25].

The outcome of their triode collaboration period generated very different, but complementary results: Appleton went no to develop the square-law detector; used his triode squegger (self-quenching, or, self-blocking) oscillator circuit in the pulse modulation mode to investigate the ionosphere [26] and; an early means of identify friendly aircraft on a radar screens. This was achieved by fitting the friendly aircraft with a transponder that received the prompt signal and sent back a coded identification signal. Van de Pol however went on to develop the non-linear LCR mathematical model of triode valve and external coupled circuit into a general dimensionless equation (i.e. having no regard to physical origins) [27]. This conceptual equation has become known as the Van de Pol oscillator and is now used in many scientific endeavours [28].

Returning to consider the triode squegger oscillating circuit, the basic circuit is shown in figure 5, which is based on the 6AG7 valve. The operation of the circuit can be considered as a series of linked stages where the phase of the transformer connection is such that the potential of the grid will become positive, which in turn will produce an increase in the anode current. For example; the anode signal is fed back to the grid using a feedback transformer to produce a regenerative action. The operation of the circuit may be best understood by first considering the action of the blocking capacitor (*Cg*) that is connected to the grid. Now as the grid draws current *Cg* is charged over the charging period and the charging of the capacitor will cease when the anode potential falls to the cut-off voltage (V_0) of the valve at which point there is no longer any voltage induced in the grid transformer winding and in consequence *Cg* begins to exponentially discharged through the grid leak resistor (*Rg*) with a time constant approximately equal to *RgCg*. The RC charge and discharge cycle then repeats itself with a total repetition period (*T*), where *T* is given by equation (5).

$$T = \tau + R_g C_g log_e \left[\frac{V}{V_0}\right] \tag{5}$$

Where τ is the pulse width at the anode, V is the voltage to which the capacitor is charged to during the pulse. Thus τ depends upon the value of the capacitor and the characteristics of the transformer. In this configuration the output oscillations consist of a short burst of oscillations separated by quiescent period where the pulse has a typical duty cycle of 25%, and as the valve of *Cg* is varied τ varies from 0.2 and 20 μs which turns out to be the ideal pulse period requirement to de-convolve the temporal variation of short wavelength signal intensity at night between direct (ground) waves and the downward atmospheric reflected wave from the upper ionosphere [29]. For further information on the squegger circuit pulse modulated waveform see references [30]. More recently, the squegger circuit has been coupled to power transistors (2N0355) has a high voltage pulse supply for atmospheric pressures plasma jets [31].

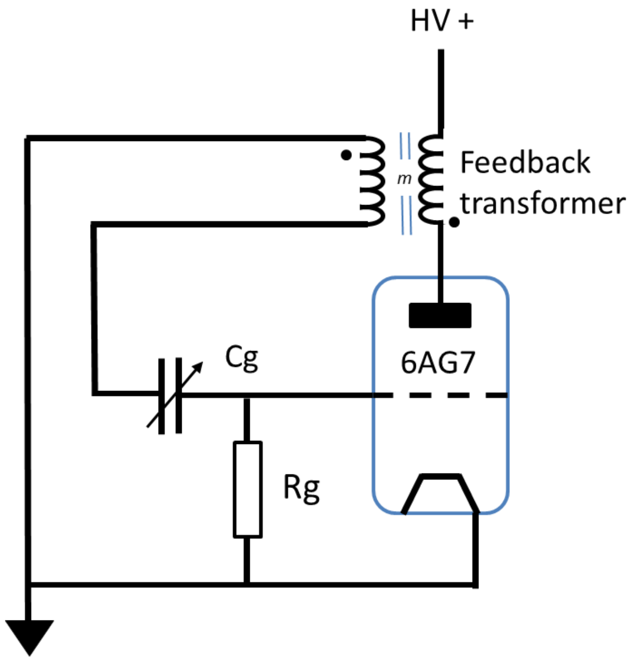

Figure 5. Appleton's triode Squegger oscillator circuit.

2.5 Electron transit time

Before we conclude this section on the triode it must be stated that the upper limit of the useful frequency range is fixed by both external circuit design and internal electrode geometry of the valve. In the case of external circuit influence the main loss contribution comes from the inductance of the connecting leads to the valve. Whereas the internal factors arise from: the losses by radiation from the valve structure, limited capabilities for heat dissipation, and the electron transit-time, that is to say the time required for electrons to travel from the cathode to anode. Careful attention to these points has permitted great progress, however, the electron-transit time presents a major challenger when build a composite electrode structure.

In the case of 'transit-time effects' this arise when an electron take a similar time to traverse the inter-electrode space, in particular the cathode-grid, when compared to that of the period of oscillation of the signal being amplified. As a result of this time difference, the appearance of a signal at the end of a valve is not followed instantaneously by the change in current flow within the valve.

The damaging effect of the electron transit-time can be either reduced by decreasing the separation of the composite grid and cathode thus the shifting limiting frequency towards higher values (typically, 1GHz (30 cm), but not without adversely affecting the available output power. An altogether and different approach would be to put the unavoidable transit-time effect to useful purpose in a new form of electronic valve.

3. Magnetron

Given the litigation problems surrounding the De Forest's triode patent, Governments and industrial companies around the world began research programs to overcome De Forest's patent and the technical limitations of the electron transit-time effect. The initial and logical outcome was not to attempt to make an amplifier, but simply to replace the grid electrode with a magnetic field to control current flow with the aim to produce space-charge oscillations travelling through the ***ExB*** field, where B is the flux density of the magnetic field. The following paragraphs provide a brief summary of the magnetron development and the modes of oscillation encountered along the way.

3.1 Retarding-field triode

The German scientists Heinrich Georg Barkhausen and Karl Kurz where the first to utilise the electron transit-time effect, in a triode valve, to velocity modulation a signal with the grid at a positive potential relative to both the cathode and the anode [32]. Under these conditions electrons emitted from the cathode are accelerated towards the positive grid, where most pass between the grid wires and approach the anode where they are retarded back to the grid and cathode. This electron dance continues back and forth through the grid until one by one they strike the grid wires. Hence the valve became called the "retarding-field triode", or "positive-grid oscillator". They found that their simple valve design could operate in the frequency region of 1.7 GHz (17.5 cm) but with only little output power. However the three characteristic effects of their transit-time triode namely; velocity modulation, bunching and power transfer from the beam to the circuit would be found later in the magnetron and klystron valve.

3.2 Coaxial diode magnetron

The Swiss-German physicist Heinrich Greinacher was one of the first to use a cylindrically anode coaxially aligned to an inner cathode with a magnetic field superimposed parallel to electrodes by a coil outside the glass envelope. Due to poor vacuum the attempt was only partially successful, but he did provided the first basic concept of electron precession within the ***ExB*** field. In 1921 Albert W. Hull at the General Electric Company published his work on his coaxial diode valve [33]. A cross-sectional schematic of his magnetron (without the external coil) is shown in figure 6a. Hull demonstrated that the strength of the superimposed magnetic field acts as a relay on current flow through the valve by restricting the electrons reaching the anode beyond a critical magnetic field strength. The mode of oscillation operation is one determined by the electron-transit-time between the cathode and anode. When operating just below the critical magnetic flux density, powers of 8 kW at 30 kHz were achieved. This regeneration frequency (f_r) follows the relation f_r = constant/$\boldsymbol{B}$, where $\boldsymbol{B}$ is the correct flux density of the magnetic field to enable electrons to arrive at the anode and the constant is related to the electron transit time between the cathode and anode and back. Hull called his tube the "magnetron": the word is the synthesis of the words magnet and electron thereby the magnetron became part of the kenotron family of valves. By 1924, the Czech physicist Napsal A. Žáček [34] developed a magnetron with a solid cylindrical anode that generated frequencies up to 1 GHz (30 cm).

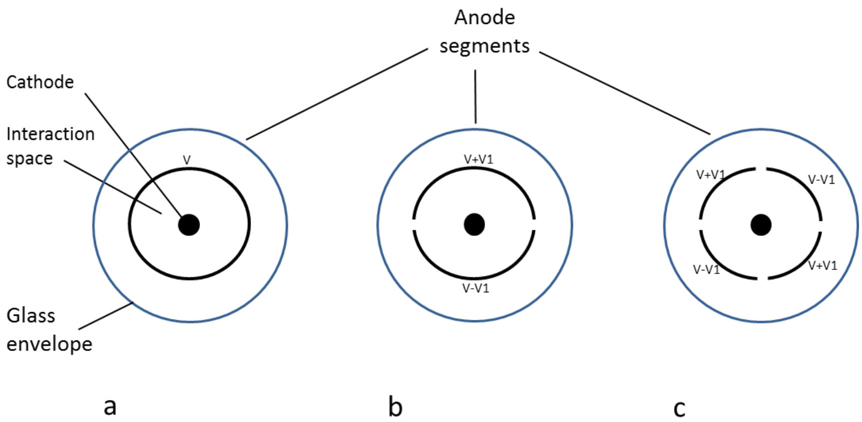

Figure 6. Cross-section schematic of the anode segmentation development. Hull's single anode (a), 2 segment anode (b) and, 4 segment anode (c). The external coil is not shown for clarity.

3.2 Coaxial split-anode magnetron

In 1924 the German physicist Erich Habann [35] produced the first split-anode magnetron. His valve had a central cathode wire surrounded by two plane or semi-cylindrical anodes, within an evacuated glass envelope, see figure 6b. Again a superimposed magnetic field parallel to the cylindrical arrangement was provided by an external coil. Using this arrangement a regenerative action of 100 MHz (3000 cm) was obtained.

After graduate study in Germany, England, and America, Japan's best-known radio researcher in the 1920s-30s was Professor Hidetsugu Yagi at Tohoku University, Japan. During this period (1927-29) one of his early doctoral students Kinjiro Okabe made the breakthrough into the centimetre wavelength using 2 and 4-segment split-anode designs (figure 6b and 6c) [36]. In both cases the principle mode of operation is not only the electron-transit-time, but also impulse or amplified negative resistance in which the frequency is equal to the natural frequency of the circuit.

Klass Posthumus famously derived a mathematical formula that related the f_r to an even number of segments pairs, n, where n = modal value of 1, or values = 2, 4, 6, so setting the scene for future development [37]. Equation (6) shows this relationship,

$$f_r \approx \frac{4\pi n V_a}{r_a^2 B} \tag{6}$$

Where V_a and r_a are the anode voltage and radius, also. Therefore for given constant V_a/B, increasing the number of segment pairs also increases f_r: which is in-line with experimental observation. The approximation term in equation (6) is used as magnetons do not generally exhibit a zero-bandwidth power spectrum [25] but contains a phase noise component of approximately 100 MHz centred on f_r. This is particularly true of the split-anode design where the anode segments are punched out with precision but with poor dimensional imprecision when fabricated together to form the composite split anode.

Crucially the opposing anode segments need to be operated at different RF potentials (V +V1 and V-V1, respectively) so that the weak electric field surrounding the gaps can deflect the electrons as they sweep past these openings and induce a resonant, high-frequency radio field. During the procession; electrons which gain energy from the RF field return to the cathode, whereas electrons which lose energy move to the anode. Also as the electrons sweep past some of electrons miss the anode and proceed to the next gap, thus receiving successive impulses as they orbit until finally arriving at the segment with the lower potential.

To simplify this argument Heller's flat plate split-anode picture is used here which introduces no changes in the principle of their action [38]. Heller's picture is reconstructed in figure 7. Here the left-hand anode has a higher potential then right-hand anode, as may be seen from the course of the equipotential lines. Its potential is not however so great that an electron leaving the cathode with zero velocity could reach the plate. When an electron approaches the gap it enters a region where the equipotential lines are bent and lie closer to the anode. The electron will follow this course, and therefore reaches the anode with lower potential although it began its journey under the anode with the higher potential.

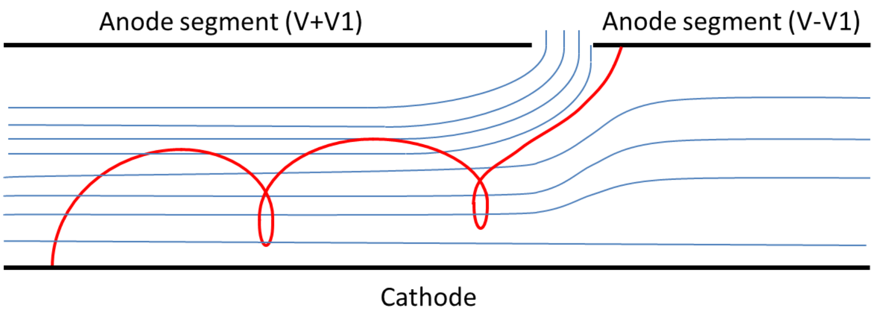

Figure 7. A reconstruction of Heller's Simplified scheme of two flat anode segments and cathode. The equipotential lines (fine blue) and electron orbit (thick red) in interaction space are shown.

By 1939, Tsuneo Ito at Tokoku University developed the 8 segment split-anode Tachibana (Mandarin-orange flower) which had a metal base with integrated water cooling within a glass envelope [39, 40]. Later, with Yoji Ito, Tsuneo developed phase opposition, or push-pull, circuit that strapped alternate segments, thus in part stabilising f_r and reducing the phase noise. The Tachibana magnetron was further developed as the type M-3 magnetron that was contained within a glass envelope using a copper block anode that had radiating cuts giving rise to the name of Kosumosu (cosmos), or rising sun. The M-3 was able to operate at 3 GHz (10 cm) with a CW power of 500 watts and predating the Randell and boot magnetron by some months, although at a greatly reduced output power. In 1941 the M-3 was productised to the M-312 magnetron, where the anode 'rising sun' design employed vanes with all the cavities uniform size and operated in pulse mode at 9.9 cm and a peak power of 6.6 k watts [40].

It is worth noting that the technique of phase opposition, or push-pull was patented by the German scientist Karl Frizz in 1938 [41]. In the patent he describes how alternate segments can be inter-connected by means of clips or connecting conductors plus the addition of an auxiliary electrode inserted into the cathode the modulation of which, by the action of the auxiliary electrode, controls the radio frequency current. Whether with or with this knowledge in 1941 the Northern Irish physicist James Sayers developed the double ring strapping system that connected alternate segments within the cavity magnetron which was further refined by Ernest. C. Okress and Robert R. Reed using the Echelon strapping system in 1957 [42].

3.3 Slot-hole cavity magnetron

Under the direction of Australian physicist Mark Oliphant at Birmingham University, Henry A. H. Boot and John T. Randall combined the ideas from researchers in the U.S, Denmark, Germany and France, to develop the multi-cavity magnetron with an electromagnetic. The French influence came from Maurice Ponte of the Compagine Génerale de Télégrahpie Sans Fil who escaped to Briton with the full permission of the French government, before the fall of France. Ponte provided the British team with the French M-16 magnetron that had a heated oxide-coated cathode and 8 cavities enclosed within an evacuated glass envelope giving peak powers of ~1 kW at 16 cm [43]. About the same time (May 1940) the British team came up with their 6 cavity multi-cavity magnetron, where the 6 cavities were drilled into a copper block using a Colt revolver as the drilling jig followed by cutting radial slots into the holes with dimensions chosen such that the resonance frequency could be calculated using the gaps as capacitors and the holes as inductors [44, 45]. Finally, the action of the ***ExB*** field in the interaction space is to synchronise the rotating beam of electrons with the anode reentrant cavities to form an electromagnetic slow-wave: the RF power from which is coupled out of the interaction space by means of a coaxial coupling loop. A schematic cross-sectional view of an 8 cavity-magnetron is shown in figure 8a.

Due to the multiplicity of resonators used (6 or 8) oscillation mode jumping occurred that resulted in the magnetron's output changing from pulse to pulse, both in frequency and phase. The modes also varied from one magnetron to another. The Northern Irish physicist James Sayers took an interest in these mode jumps. Experimentally he found that there was a phase difference between adjacent resonators of π radians or 180 degrees. Neighbouring resonators are thus in anti-phase and successive anode openings facing the interaction space produce a clockwise rotating electric field. Moreover, under the influence of the ***ExB*** field the electrons become bunched in a spoked wheel formation (3 spokes for 6 cavities and 4 spokes for 8 cavities) directed time after time to the nearest positive anode segment with an angular velocity around the cathode of 2 segments per cycle, see figure 8b. The modes are designated by their modal number, *n*, defined as the total electrical phase change around the anode block measured in revolutions, or by phase difference (ϕ) between successive segments. The relations of these two quantities (ϕ and n) for a given anode block of N segments may be expressed as in equation 7.

$$\phi_n = 2\pi n \tag{7}$$

Where the largest value of n is N/2 and is called the π-mode, as the ϕ = 180 degrees and is the most nondegenerate (stable) mode. To stabilize the π-mode two concentric metal rings are used: the first ring is connected to even number segments and the second connected to odd number segments, thus each ring connects to alternate segments. The procedure is called termed “π strapping” because the double-ring straps lock the phase difference between adjacent segments, thus separating and selecting the π-mode from neighbouring resonant modes within the mode spectrum.

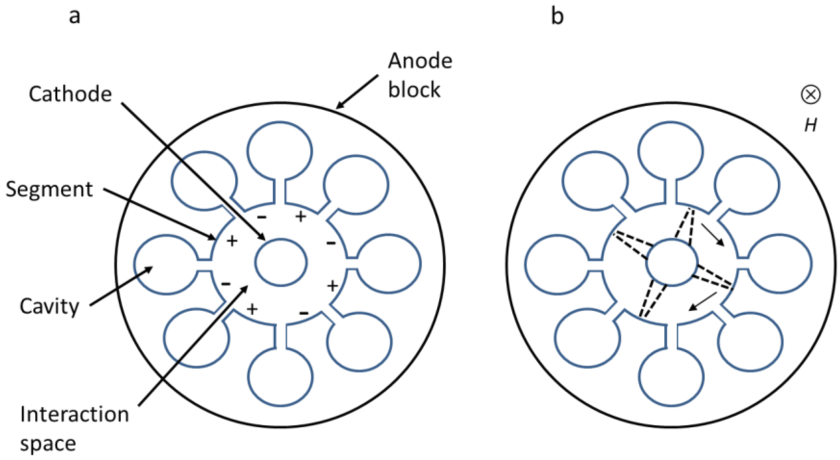

Figure 8. Magnetron; a) cross-section of N = 8 cavity magnetron and, b) the space-charge wheel rotating about the cathode with the magnetic field is going into the page.

The removal of all external tuning circuits in the Birmingham cavity design is more than compensated when you consider that a few watts of almost spurious radiation was turned into 100 kW of well-defined signal generated by a compact practical device. The cavity magnetron advantages can be listed as: the removing the complex manufacturing process of the anode segments and replacing it with a single copper-block that reduces segment miss-alignment and improved anode surface smoothness, the enablement of the vacuum to be inside the anode structure thus removing the need for a glass envelope. These advances over a short period time produced a near all metal design that allowed the efficient cooling for higher heat dissipation as compared to previously patented magnetron designs. Moreover the light-weight design enabled centimetre radio detection and ranging (RADAR) sets to be made airborne and seaborne thus fulfilling Robert A. Watson-Watt and Arnolds F Wilkins memorandum: *The detection and location of aircraft by radio methods* [46].

3.4 Tizard mission

Arguably the Tizard mission (British Technical and Scientific Mission to the United States of America and Canada) changed the technological course of WW2 in the late summer of 1940; the aim of the mission being to obtain industrial resources and exploit the military potential British research and development up to that point. Tizard's "brief case" therefore held the sealed-off magnetron type E1189, series N.12 developed by E. C. S. Megaw at GEC, enigma code breaking information and all what Britain knew about building an atomic bomb As regards to the said magnetron, the American's scientists Xrayed it and found 8 cavities whereas the accompanying drawings stated 6 cavities thus giving rise to suspicions. Megaw was telegraphed and after a short time was able to remember that the first 10 magnetrons had 6 cavities and number 12 had 8 cavities, immediately the drawings were updated and a developing international incident was avoided. For this extraordinary mission, Britain would receive financial and industrial help for their war effort. By September, the Massachusetts Institute of Technology (MIT) had set up a secret laboratory; by November, the cavity magnetron was in mass production; and by early 1941, portable airborne radar had been developed and fitted to both American and British planes with pulsed transmitter powers of ~100 kW at 3 cm in 1940 to ~2 MW at 10 cm by 1944.

To place the secrecy and the success of the Tizard mission into context, it was not until February 1943 that a high power 10 cm magnetron and a reflex klystron fell out of the sky into Germany's hands. This came about when a Stirling bomber was shot down near Rotterdam with its secret H2S radar equipment virtually undamaged. Germany made an almost exact copy which they named the "Rotterdam Great" [47]. Inevitably similar occurrences happened in the pacific in 1945 when B29 bombers were shot down [48]. Fortunately for the Allies the capture of the centimetre radar secret came too late to have any significant effect on the outcome of the war.

3.5 Magnetron self-resonant frequency stability

In sections 3.1 to 3.4 this paper has mainly focused on the magnetron's mode of operation with little discussion on its self-resonant frequency stability. We now turn to this subject by comparing experimental and theoretical analyses of the split-anode magnetron and experiments conducted to reduce the spectral noise bandwidth of cavity magnetrons.

First consider the split-anode magnetron based on the 1936 published work: *Discussion on "the action of a split-anode magnetron"* [49]. In this work the contributors (Messrs. H. Awender, D. M. Tombs, E. C. S. Megaw, E. W. B. Gill and K. G. Britton) considered the space-charge production surrounding the tungsten-cathode and its bombardment by electron returning from the neighbourhood of anode segment gaps. For example, it is appreciated that the electrons leave the heated cathode filament with the near-same velocity of emission to form a space-charge region that surrounds the cathode, beyond which the electrons gain energy as they spiral though the ***ExB*** to the segmented anode. In this region the ideas of precessional resonance between the electron orbits and the standing wave of potential round the anode segments were established. Thus when electrons transit a segment gap some will be retarded and spiral out towards the most negative potential anode segment, while those electrons that gain energy are accelerated towards the cathode. In other words electrons reaching the anode regenerate the oscillation, but electrons retuning to the cathode do not. Moreover the retuning elections must move though the space-charge region, thereby temporarily disrupting the space-charge current before bombarding the tungsten-cathode and heating it further thus contributing to the split-anode magnetron's spectral bandwidth output.

Turning to the cavity magnetrons that utilize a heated oxide-coated cathode, its spectral noise bandwidth has been shown to be significantly reduced by a number of means, three of which are presented here. Firstly, the spectral noise is a reduced using a magnetron which is operated by a dc stabilized power supply and whose filament current is turned-off when the oscillations start [50]. Azimuthally varying axial magnetic fields may also be used to reduce spectral noise at all anode currents, but is particularly significant at low current near the start-oscillation condition [51]. Thirdly, metal shielding of the HV input side of the cathode can equally reduce spectral noise [52].

The above discussion of the split-anode and cavity magnetron may be considered to have been reported in the Welch and Dow paper of 1951 [53] where it was proposed that the spectral noise originates in the cathode as thermal noise and ionization of atoms of the cathode oxide coating by electron back-bombardment, both of which are amplified by the continuous interchange of energy between the dc field of the space-charge region and the electromagnetic field that is present within the interaction space. Welch and Dow also went on to theorise how spectral noise could be measured and reduced: references [50 - 52] provide experimental confirmation of their theories.

4. Sputter ion pumps and the plasma etch reactor

This review now turns to the Varian brothers (Russell and Sigurd Varian) who developed the first American Klystron amplifier in 1939 [54]. The name klystron is derived from two Greek words: klys (the Greek verb referring to the breaking of waves on a beach) and tron (device, instrument, or a chamber where something happens). The klystron was first described in Germany 1935 by Agnesa A. Heil and Oskar Heil, titled: *A new method for producing short, undamped electromagnetic waves of high intensity* [55]. Once married, Agnesa and Oskar moved to Britain to work in the Cavendish Laboratory, University of Cambridge. At the onset of WW2 Oskar returned to Germany via Switzerland to complete the development of his microwave oscillator at Standard Lorentz and subsequent devices were used in airborne and surface microwave radar by Germany [47].

Arising from their studies during the war the Varian brothers who worked at both MIT and Stanford University fully understood the necessity of clean vacuum technology for the manufacturing of magnetrons, television tubes, cathode-ray tubes and their klystron. After the war they looked for a viable low cost non-military use of their clean vacuum pumping knowledge. With this in mind they set about tackling the problem of achieving high vacuum and contamination free pumping for the valve industry. In mid-1950s their first commercial electronic vacuum pump was the diode sputter-ion pump (diode

SIP) and it became a major success virtually overnight. Oil pump vapour attaching to the inside of the electronic valves at the evacuation process stage was now a problem of the past. We now move on to electronic valves that have been deliberately designed to have their ion space-charge interact with the valve body and where the thermionic emission source is replaced by either a high voltage dc (kV) supply, or by radio frequency (RF) excitation. The electronic valves described in this section operate between low vacuum and ultra-high vacuum (UHV) thus plasma generation and space-charge is possible. The electronic valve designs take full advantage of sputter observations of Grove and Guthrie [7, 8], Hammer's phantom shadow and Child's Law [18]. The development of the diode SIP system firstly helped to address high vacuum pumping instabilities. This is followed by two open flow plasma-etching reactors designed for pattern-transfer, these are the: diode parallel-plate reactive ion etching (RIE) system and the triode plasma etch system.

4.1 Diode sputter-ion pumps

As described above the Varian brothers developed the diode SIP that is based on Grove's and Guthrie original observations [7, 8]. In these pumps a titanium cathode is used because of its high reactivity with N_2, O_2, H_2O, CO, but not inert gases. The scavenging, or getting, of these gases makes the pump ideal in establishing a 10^{-11} Torr UHV environment in electronic vacuum valves and other evacuated process chambers such as molecular beam epitaxial growth chambers [56].

The diode SIP basic construction consists of a central honeycombed anode plate operated at about 7-10 kV surrounded on two sides by a split titanium cathode that is fixed at ground potential. In addition an external permanent magnet is employed to produce a magnetic field orientated along the axis of the anode to form an ***ExB*** field between the electrodes. The complete pump is attached to the electronic vacuum valve, or, process chamber that is being evacuated. A typical cross-section schematic of the diode SIP is shown in figure 9a. The ***ExB*** field between the anode and cathode form a Penning trap (named after Frans M. Penning by Hans G. Dehemlt who built the first trap [57]) where electrons are temporally confined to improve the ionization rate of incoming atoms and molecules, see figure 9b.

The pump works by capture, that is to say converting gas into solid compounds. Under high voltage, the cathode emits electrons and, due to the presence of the magnetic field they move in helical trajectories to the anode. These electrons ionize the unwanted incoming gas atoms and molecules which are then accelerated to strike the honeycombed cathode. On impact the accelerated ions either become buried within the cathode or the cathode material is sputtered, distributing cathode material throughout the pump. The freshly sputtered titanium material acts as a chemisorption and physisorption getter. This getting process facilitates the achievement of high vacuum.

Earlier in this paper, it was noted that chemically neutral argon gas comprises approximately 1% of atmospheric pressure air. Therefore it should be no surprise that within the pump the argon capture mechanism is by burial (physisorption) only. It was Robert L. Jepsen and co-works at Varian that first noticed that after prolonged operation on an air-leak, some of the previously buried argon is periodically reemitted as high-energy neutral argon gas so causing a cyclic pressure rise [58]. This cyclic "Argon instability" releases material causing a rapid pressure rise, up to the point where the pressure reaches about 10^{-4} Torr. As the argon is slowly pumped into other areas of the pump, the pressure falls again with the discharge changing to a more diffuse mode before shifting back into the confined Penning trap that is more efficient in sputtering. Thus the process begins to repeat the pressure cycle with fluctuations between the base pressure and the outgassing pressure. The precise nature the instability (whether cyclic, continuous desorption and saturation) is control by the voltage, current and geometry of the pump [59].

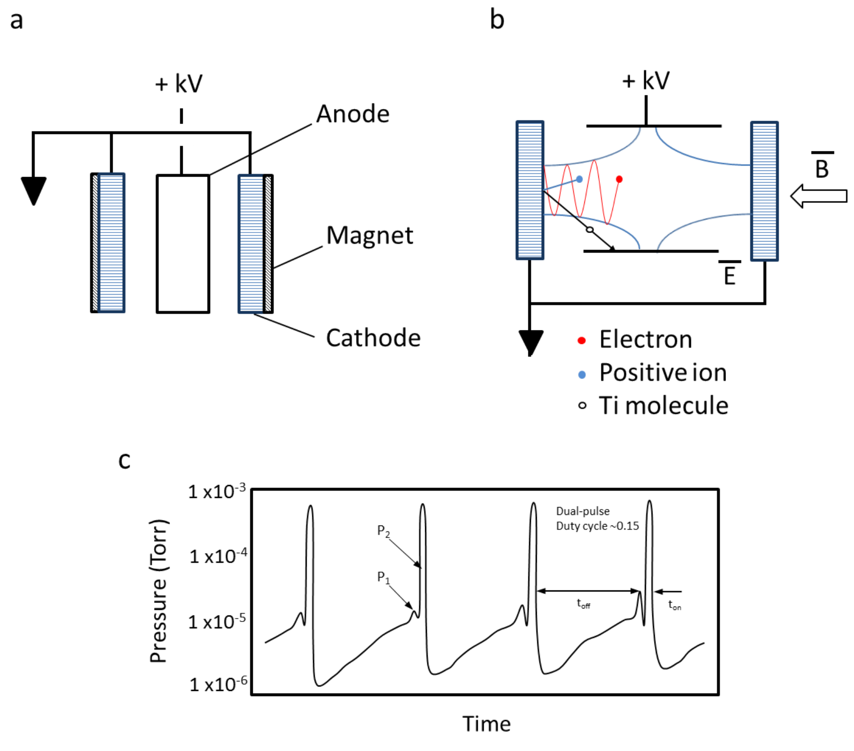

Figure 9. a) cross-section of diode-SIP, b) Penning trap and, c) typical time trace of a cyclic argon instability.

Some 45 years after the original observation, Tommaso Perclli et al (using scanning electron microscopy and energy dispersive x-ray) have suggested that the formation of sputtered titanium micro-cones at the cathode surface play a leading role in the onset of the instability phenomena in different gas burial sites [60]. Figure 9c shows a typical instability (see Jepsen [58]) as a function of time. In this example the time trace has a dual-pulse periodic instability with a duty cycle, D, [25] (D = dual-pulse on time (t_{on}) divided by the total time period of wave) of approximately 0.15, where the dual-peak ratio (P_1/P_2), averaged over 4 periods, is 0.02 ±0.02. Note also there is a gradual pressure rise between the pulse-off (t_{off}) time periods. In this example the time intervals between the dual-pulse pressure fluctuations are typically several minutes at a pressure of 1×10^{-5} Torr, and vary approximately inversely with leak rate for pressures in the range 5×10^{-7} to 1×10^{-5} Torr.

When a typical cyclic "Argon instability" is compared with the oscillations in the Appleton's triode squegger oscillator circuit, some similarity in their pulse shape is evident even though their production mechanisms are very different in nature: i.e. sputtering of buried material, as compared to external circuit RC time constants. This difference is exposed in their oscillation frequency: 10^4 to 10^6 Hz for the squegger; and sub Hz for the "Argon instability".

As there is no equivalent electrical model of the "Argon instability", it is reasonable to devise a simple mathematical model that can represent one or two pressure peaks per instability cycle. This is achieved by using two coupled ordinary differential equations to mimic the dynamics of gas burial and reemitted gas instability. The two equations are executed using visual basic for applications (VBA) functions within an Excel programming environment. Equations (8) and (9) show these lines of code.

$$\frac{dx}{dt} = b * y - x^3 \tag{8}$$

$$\frac{dy}{dt} = -x + a * \sin(\omega * t) + d \tag{9}$$

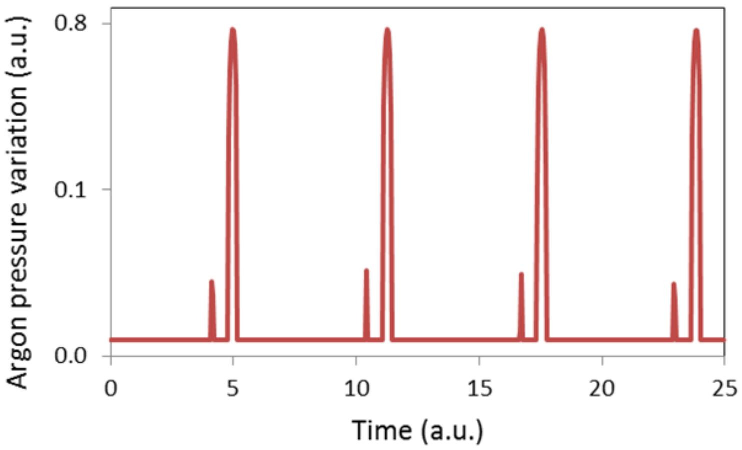

Figure 10. Simulation of a cyclic argon instability using the coupled differential equation averaged over 4 periods. The following wave parameters are: a =1.83; b = 50; d =-2; ω =1.

Where *dx/dt* and *dy/dt* are the instantaneous rate of change of *x* and *y* with respect to time; the cubic power assigned to *x* ensures a discontinuity containing at least two peaks in the wave function; *a*sin*(*ω*t*) is the driving function, where *a* is the amplitude of the wave function and *ω* is its angular velocity with respect to time and is set to a non-harmonic relationship of 1; finely *b* and *d* are the experimental variables, where *b* controls the relative peak amplitude of the dual-peaks and *d* positions the dual-peaks in the x-axis and therefore is related to the duty cycle of the wave. To take in account the pressure Log scale and heterogeneous nature of the instability, negative values of the oscillation are coerced to 0.01, below which represents gas burial. The coercion is performed using the VBA code: =MAX(0.01, *reference cell*).

Figure 10 shows the Excel simulated results for x (argon gas pressure) at fixed values of: a = 1.83, b = 50, d = -2, ω = 1. For this simulation, the instability (averaged over 4 periods) has a duty cycle of D = 0.21 ± 0.03 and P_1/P_2 ratio = 0.03 ±0.003, respectively. This simulation provides a general qualitative characterisation of the instability for given data in figure 7, including a quantitative match for the dual-peak ratio.

Vaumoron and De Biasio have also shown that a diode SIP with a mixture of tantalum and titanium cathodes pumping a continuous leak of xenon can produce a singlet of cyclic ‘instabilities [59, figure 1]. Therefore the same form of coupled differential equations needs to produce a single peak. This is achieved by reducing the value of *a* to less than 1.82, or by reducing the value of *b* to 25 whist keeping all the other parameters constant. However it should be noted that the model, at present, does not provide an increase in the base pressure between the pressure peaks thereby indicating that the model requires further investigation for continuous and saturation instabilities.

4.2 Triode sputter-ion pumps

In 1959, Wilson M. Brubaker developed the triode ISP [61] and subsequently follow-up by further improvements by Jepson in 1967 [62]. The pump is configured with the anode split into three plates (a central and two outer auxiliary plates) all of which are fixed at a ground potential. Using the same relative voltage difference as the diode, high voltage (kV) is counted to a dual split-cathode, but the plates are positioned to keep the three anode plates separated.

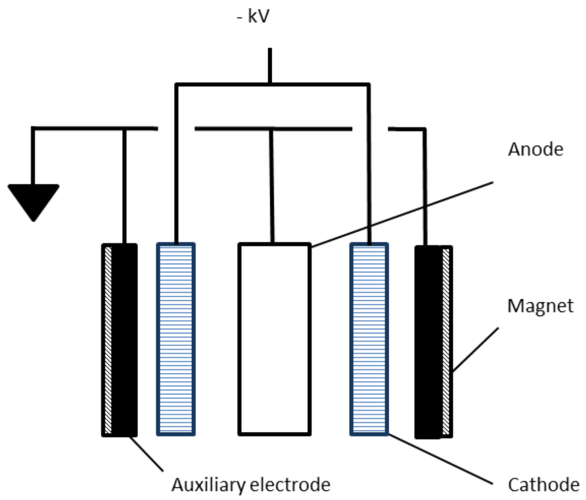

Figure 11. Cross-section of triode SIP.

A cross-sectional schematic of the triode ISP is shown in figure 11. In this configuration energetic ions bombard the cathode grids under glancing incidence with a high sputter yield of titanium. The additional effective area of the third electrode greatly enhances the pumping action of the discharge for inert gases. Moreover the energetic neutrals created by ions impinging on the cathode grids hit the auxiliary electrode or are reflected back and buried in the anode with few, or no, ions reaching pump body or anode. With these modification noble gases remain buried which leads to a reduction in pumping instability action.

4.3 Diode asymmetric parallel-plate RIE reactor

The diode asymmetric parallel-plate RIE reactor is another manifestation of the electronic valve. In this work, the shorten term: reactive ion etching reactor, or RIE reactor, is used. The process has its conceptual origin in 1960s when Harold S. Butler and Gordon S. Kino showed mathematically that when an RF (typically 13.56 MHz) voltage is connected to a cylindrical electrode that surrounds a glass reactor containing a low vacuum (1-40 x10^{-3} Torr) gas, the resultant luminous portion of the plasma discharge is constricted away from the inner walls of the glass tube, leading to the formation of an ion-rich sheath [63]. It should be pointed out that the RF confinement mechanism includes a dc component, rather than the pure RF confinement as proposed by Boot, Self and [64]. By the 1970s the ion-rich sheath phenomenon was developed to meet a new and urgent need to anisotropically etch fine-line electrical circuits in silicon microchips [65 - 70].

As in the diode valve, the RIE reactor configuration has two electrodes: one fixed to ground potential and the other electrode is driven via external capacitor from the RF generator. The purpose of the external capacitor is to block dc current flowing and induce RF rectification that forms a negative self-bias at the RF driven electrode. In a large number of RIE reactor external circuits, the blocking capacitor also forms the last series element of the impedance matching network that connects the 50-Ohm RF generator output to the non 50-Ohm plasma dynamic impedance, which results in unstable voltage oscillations and harmonics within the ion-rich sheaths, that cannot be controlled by the external RF circuitry [71, 72].

At the driven electrode a greater number of higher energy positive ions are developed with respect to the ground electrode. To enhance the positive ion bombardment effect the RF driven electrode area (A1) is made smaller than the ground electrode area (A2). Therefore, for etching purposes, the material to be etched is placed on the driven electrode. A schematic of the RIE reactor and external blocking capacitor is shown in figure 12.

Harold R. Koenig and Maissel [65] where one of the first teams to mathematically examine the voltage division of two different diameter planar sheaths with a fixed inter electrode distance using the collisionaless version (~1 x10^{-3} Torr) of the Child-Langmuir Law. Their analysis revealed that the larger voltage appeared on the smaller electrode with a fourth power law dependency, see equation 10.

$$\frac{V_1}{V_2} = \left(\frac{A_2}{A_1}\right)^4 \tag{10}$$

For the RIE process which generally works in the 10-20 x10^{-3} Torr pressure range the fourth power dependency does not hold due to many more collisions within the sheath, hence the power dependency falls with pressure to value of 1.0 to 1.5. This high pressure dependency range is known as the mobility-limited or ionisation-limited Child-Langmuir Law. Rossmaien *et al* [73] have also shown that the self-bias voltage increases as a function of RF power with proportionality slightly more than the square root and increasing the pressure lowers the self-bias.

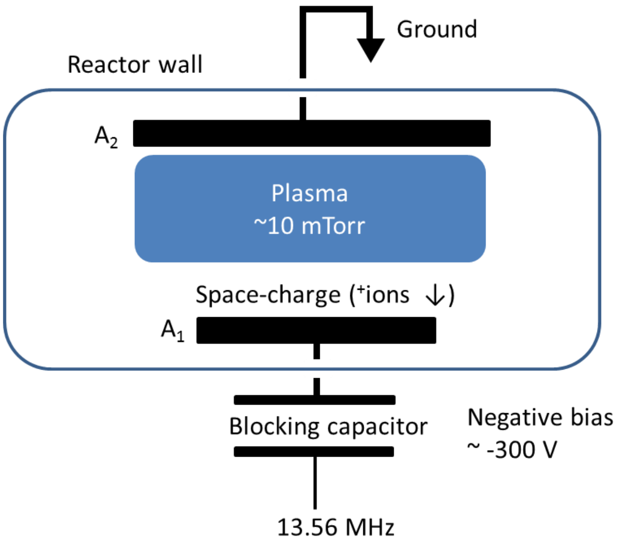

Figure 12. Cross-section of a typical RIE reactor, with external blocking capacitor and driven at 13.56 MHz.

In the RIE process itself, neutral atoms, molecules and ions each play an important role in the etching and deposition process. In the case of high energy positive ions they strike the target material at a near perpendicular angle with sufficient energy to sputter enhance the etch process and facilitate the formation of an anisotropic etch profile.

To comprehend how the RIE process works, the metal-organic reactive ion etch (MORIE) process of III-V semiconductor material is considered. In particular how the etch precursor gas (in this case; methane (CH_4) and hydrogen (H_2)) forms two competing modes of plasma-surface behaviour when anisotropically etching gallium arsenide (GaAs). For the following process parameters conditions : power density = 1.1 W cm^2, self-bias = -600V and a total gas pressure 10 x10^{-3} Torr, the modes for "RIE" [74] and "gas phase polymerisation" [75] are represented here as feasible heterogeneous thermodynamic chemical reactions between the precursor gases and the substrate surface.

For the RIE mode, the representative balanced stoichiometric equation for GaAs may be written as in equation (11):

$$3(CH_3 - H) + GaAs\,(s) \xrightarrow{rf + H_2} (CH_3)_3 - Ga + AsH_3 \qquad (11)$$

In this equation the solid GaAs surface is converted into highly volatile by-products (group III metalorganic and group V hydride: trimethylgallium and arsine), all of which are evacuated from the GaAs surface by the reactor vacuum pumping system.

For the gas phase polymerisation mode (with reduced or no H_2 presents), the representative balanced stoichiometric equation GaAs may be written as in equation (12):

$$3(CH_2 - H_2) + GaAs\,(s) \xrightarrow{rf} (CH_2)_3(s) + GaAs(s) + H_2 \qquad (12)$$

Here the plasma-surface reaction tends towards methyl polymer group non-volatile (solid) by-products that form on the GaAs surface so preventing the etching to take place.

It should be noted however, that due to the open flow reactor design the point at which the mode jump occurs between etching and deposition will be controlled by the rate-limiting step within the GaAs surface driven transport kinetics: in this case the vapour pressure of the etched products [76].

4.4. Triode plasma etching systems

Before leaving this section on space-charge and plasma reactors it is worth noting that Victor J. Minkiewicz and Brain N. Chapman at IBM Research Laboratory, San Jose, California first reported on the use of the triode sputter etcher in the late 1970s [77]. For a more in-depth discussion on the triode plasma etching see also [2].

These reactors where popular in the 1970-80s before being superseded by hybrid reactors: the electron cyclotron resonant reactor [78, 79], downstream microwave [80] and inductively-coupled reactor [81]. These Hybrids introduced electrical power into the reactor through a secondary source that can lead to mode jumps and instability regimes. In today's semiconductor and Nanotechnology industries the control and characterisation of mode changes and instability are mapped in state-space has become the norm.

5. Summary

This paper has bought together for the first time (in the author's knowledge) the technical developmental stages of the electronic valve (lightbulb, diode, triode and magnetron) and the technical and human challenges that had to be overcome. It has been shown that these electronic valves are well studied from a physics and electrical engineering point of view of establishing the required hard vacuum pressure of 10^{-7} Torr, or less, for the valves thermionic emission to generate 'hot' negatively charged electrons that travel ballistically (without collision) from the heated cathode to the positive anode. Under these conditions, the electrons generate a space-charge that limits the conduction current. Instability regimes and mode jumps have been identified in each of the electron valves. The instabilities deriving from insufficient air evacuation causing hetero-charged carriers derived from gas impurities and the influence of external circuity coupling have been described. The dynamics of the triode with an external feedback circuit, as described by Van de Pol, has been highlighted. In the case of the slot-hole cavity magnetron: reentrant feedback between the cavity holes and the interaction-space, and cathode thermionic emission has been identified as sources of mode jumping and instability. The vane rising-sun magnetron is known to perform in similar way [82] but is not discussed here due to paper length limitations: a follow-up is in preparation.

These early electron valves have been placed in context with their contemporary counterparts that operate over a wide vacuum pressure range (1 x10^{-3} to 10^{-11} Torr) or at low vacuum pressure (1-40 x10^{-3} Torr). In the case of the diode SIP, gas atoms and molecules are ionised to achieve improved vacuum but is hampered by inert gas instabilities. A coupled differential equation is proposed and used to approximate the observed characteristics of argon and xenon cyclic instabilities. Whereas in the RIE reactor, mode jumps in the form of etching and deposition has been characterised using representative balanced chemical equations for the MORIE process.

Finally, throughout this paper gas impurities have been shown to provide a major source of electron valves design malfunction, whether as background gas partial pressure in the case of the electric lightbulb, the diode valve and the triode valve. Pumping of inert argon in the diode SIP and hydrogen admix gas ratio in the MORIE process have also been identified.

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