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The Impact of Receiving Tubes on Broadcast and TV Receivers*

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Summary—**The receiving electron tube has been primarily responsible for the modern superheterodyne, with its high sensitivity, high selectivity, automatic gain control, and ease of tuning. In examining the history, one finds an early period of triodes and diodes (1907 to 1927), a second period (1927 to 1936) of indirectly heated cathodes and multigrid tubes, and a third period (1936 to 1960) of close-spaced tubes and VHF operation. The most significant tube concepts are the triode, the multigrid tube, and the indirectly heated cathode, all of which started in the first period. The second and third periods were marked by tremendous advances in the technology of production, and in extensive application of the early inventions to new receiver designs. At present, solid-state devices are gradually supplanting vacuum tubes in some receiver applications, and this trend is expected to continue.**

INTRODUCTION

THE HISTORY of the receiving electron tube, and the history of the Institute of Radio Engineers are almost coincident in time. It was only eight years after the invention of the Fleming valve, and six years after the invention of the DeForest triode, that the Institute was founded in 1912. In the present survey, the highlights of tube development, as they affected broadcast and television reception, will be outlined. The five decades which have elapsed saw the early and rapid rise, a peak period extending through the introduction of television, and a saturation point with a gradual decline, as solid-state devices became more and more prominent. For convenience, the discussion will be largely chronological and is divided into three historical periods.[1] A concluding section will give a brief view of the present period, and of future trends.

The first historical period was from roughly 1907 to 1927, when only filament-type triodes were widely used. This period included the invention and application to receivers of cascade amplification, regeneration and oscillation, heterodyning, and the superheterodyne. All these basic circuit principles are still with us today, and all were made possible by the electron tube. Some other developments of the period, superregeneration and reflex amplification have never been widely used in broadcast or television reception.

The second major period is the shortest in time, and is possibly the most outstanding, so far as rate of receiving-tube development goes. It started about 1927 with the delveopment of indirectly heated cathode tubes (and a few years later of multigrid tubes), and ended about 1936 with the octal base metal tube and beam power tube. The tube developments of this period were pri-

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[1] The author wishes to apologize in advance for the many important and excellent contributions, particularly those of foreign origin, which he has been forced to omit in a discussion of this length.

marily responsible for the application in receivers of ac operation, high-level detection, very selective and single-knob tuning, the built-in loudspeaker, automatic-gain-control, tuning indicators, and multiband operation This was also the period in which the superheterodyne became the universal receiving circuit. Once again, every one of these receiver improvements remains with us thirty years later.

The third major period, from 1936 to about 1960, started with close-spaced (high gain-bandwidth) tubes and miniature glass envelope types, ending with the color picture tube and tubes for hybrid transistor-tube combination receivers. This is the period of VHF, *i.e.*, FM and television; the tube developments made these possible, together with their special circuits such as limiters, discriminators, automatic-frequency-control, saw-tooth deflection, synchronization, inverse feedback, wide-band amplification, and multiplexing.

It is unlikely that there will again be a period in which the device we know as a receiving tube will have as revolutionary an impact as in the three periods summarized above. The present and future of broadcast and television receivers appears to depend more and more strongly on solid-state methods, micro-electronics and other newer technologies. There will always be some exceptions, possibly in color picture tubes, or in tubes for higher-frequency operation of broadcast services.

The Years of the Diode and Triode, 1907–1927

The Fleming diode [1] of 1904, and the DeForest triode [2], invented in 1906, were used in radio receiver circuits shortly thereafter. Prior to 1912, the triode (Audion) was used exclusively as a detector, and showed marked superiority over other radio detection methods. The first Audions were highly nonuniform, and had a very poor vacuum. In fact, DeForest as late as 1915 said he could not predict whether the anode current would go up or go down when a signal was impressed; each tube was different [3]. However, starting in 1912, both General Electric Company and Western Electric Company scientists learned to make well evacuated and uniform tubes [4]. By 1915 Langmuir described high-vacuum tungsten-filament diodes and triodes [5], and the Western Electric telephone repeater tubes with oxide-coated filaments were already in use in cascade audio amplifiers.

These early triodes first made practical the cascade amplifier [6], the triode oscillator [7] and the regenerative feedback circuit [8]. In turn, the triode oscillator made possible application of the very important but unused principle of heterodyne reception, invented by Fessenden years before [9] when only arc generators were available. During World War I, both the General Electric and the Western Electric Companies manufactured substantial numbers of receiving tubes, of which the Western Electric VT-1 tube was perhaps best known.

The stimulus of the war led to the invention of the single most important receiver circuit to this day, the superheterodyne [10], [11]. Triode RF amplifiers had been rather unsuccessful except at very low frequencies. Major Armstrong tried to devise a more sensitive receiver, to detect enemy aircraft by their short-wave ignition noise. It then occurred to him [10] to use the heterodyne principle to lower the incoming frequency to a value which could readily be amplified, but which was still high enough to use selective circuits, at what we now call the intermediate frequency. In Germany, the same invention was made, and at about the same time [11]. Although it is obvious that the triode tube, used as an oscillator, as a heterodyne mixer, and as an amplifier, was essential to the superheterodyne, another important impact of the triode was to make possible multiple tuned circuits [12], separated by nonreciprocal active elements.[2]

World War I also stimulated the invention of the second most important electron-tube principle, the use of another grid interposed between control grid and anode, as made by Schottky [13]. Schottky saw the significance of the reverse-phase ac swing of the anode in reducing the cathode current excursion, and he devised the screen grid, at a fixed positive potential, to screen the cathode region from anode fluctuations. At the same time, he also saw that a fixed-potential positive grid between cathode and control grid (space-charge grid) could be used to greatly increase the tube current, if low voltages only were available [13a]. Two- and three-grid tubes were made in many laboratories, and went into modest production in Europe, but the tremendous advantages of the screen-grid principle for both RF amplification and for increased audio output were not widely appreciated at first. About 1926 Hull and Williams described their highly shielded two-grid RF amplifier tube [14] and research laboratories also began to experiment with pentode (*i.e.*, 3-grid) tubes for audio use, and the suppressor grid was invented [15]. A few years later, as we shall see, the screen-grid principle was used in almost every new tube type. However, in this first period of our history, tube manufacturing techniques were only just about reaching the point at which a multigrid tube could be considered; receiver designers had to make do with the triode.

An important help to the receiver designer who had to use triodes for RF amplification was the analysis by Miller [16] and others, of the feedback due to grid-anode capacitance. One proposed solution was the use of a neutralizing or cancelling type of feedback [17], a principle which was later extensively used in the Hazeltine Neutrodyne circuit [18]. Another invention of a completely different kind, was thought to eliminate entirely the need for extensive use of RF cascade amplification,

[2] Only after the perfection of the screen-grid tube was almost complete unilateral amplification achieved.

namely superregeneration [19]. However, many triode RF amplifiers used simple resistors in the grid circuit to prevent oscillation; in superheterodynes, very low IF was used. In all RF cascade triode amplifiers, stage gain was quite low, perhaps 10 to 15 db.

Up to 1920, there were no receivers in the hands of the general public, but by 1923 the broadcast receiver business was flourishing [20]. Among the available tubes were the type 200, a "soft" detector tube, and types 201 and 202 which were high-vacuum amplifier types, all with tungsten filaments. Because electron tubes were expensive, crystal receivers, or one-tube regenerative sets, with earphones, were the rule. About this time, the General Electric Company started manufacture of the '99 and the '01A triodes [21], with thoriated filaments, and the Westinghouse Company introduced the WD-11 oxide-coated filament triode [22]. The reduced filament power of these types was a great advantage to receiver designs, which were battery operated. The reflex type of circuit was devised to hold down the number of tubes, since a single tube was used as both RF and audio amplifier. Gradual reduction of tube prices over the next decade eliminated the economic need for either superregeneration or the reflex circuit, and they soon become obsolete. The Neutrodyne [18] type of tuned RF receiver with '01A tubes became very popular in the early days of broadcasting in spite of the use of a separate tuning knob for each stage. Superheterodyne receivers with six tubes were finally put on sale [23] in 1924 and this type of receiver rapidly developed a reputation for sensitivity and ease of tuning.

As the first period came to a close, elimination of "B" battery operation by means of gas-filled or high-vacuum double-diode rectifiers became common. The demand for higher audio output led to use of higher power or low-mu triodes (types '12, '20, '71, and 210) in the output stage; even so, outputs of under 500 mw were common. At this time, also, a large number of receiving tube companies began to compete strenuously for the increasing volume of business, which attained 67 million dollars per year (1927), for receiving tubes [25].

AC Operation and the Multigrid Tube, 1927 to 1936

Although complete ac operation was feasible with filament-type tubes, further advance in circuit design required the equipotential or indirectly heated oxide-coated cathode. Such a cathode had been invented many years before [24], but high manufacturing cost and great difficulty in controlling heater-cathode leakage prevented its commercial use. The first reasonably reliable indirectly heated triode was the 2.5-volt heater type '27 which was announced in 1927 and adopted by most receiver manufacturers [26]. For a year or two, a companion tube for triode RF amplification, the type '26, which had a low-hum oxide-coated filament, was also used [26]. However, it quickly became apparent to tube manufacturers that all but output tubes would soon require indirectly heated cathodes. The first screen-grid tube, the filament type '22, was also introduced late in 1927, but received almost no use. By early 1929, the 2.5-volt heater, type '24, screen-grid tube became available [27] and began to be used extensively.

Complete ac operation was the key to tremendous improvement in receiver performance from 1927 to 1930. It became practical to use many tubes in a receiver without impractical battery drain. RF amplification and high audio output led to very selective and sensitive receivers [27], [28] capable of operating the newly introduced electrodynamic loudspeakers. Along with the indirectly-heated screen grid and triode tubes, the low-mu, oxide-filament type 45 was commonly used for audio output [29]. The typical 1929 high-performance set used two or three stages of tuned radio-frequency, with screen-grid tubes and a single tuning knob, followed by a high-level linear detector and a triode audio stage with one or more type 45 output tubes, delivering from 1 to 3 w to the speaker. It was at this time that some earlier ideas, the self-bias resistor, and the automatic-volume control principle [30], began to be widely applied [31].

By 1930, superheterodynes with type 24 tubes for the RF and IF amplification began to greatly out-perform the tuned RF sets, particularly for selectivity above 1 Mc. Broadcast stations increased power enough so that cross-modulation became a serious problem and the variable-mu tube (remote cutoff) was invented [32] and appeared in receivers as the screen-grid 2.5-volt heater type 35. The output pentode [33], already in use in Europe, was introduced in the U. S. by one of the smaller tube manufacturers, Arcturus [34], and the similar type 47 soon superseded the old low-mu triode type 45 as the most popular output tube. In the meantime, automobile receivers were introduced and a 6-volt heater line, in a small glass envelope, became available as the types 36, 37, 38 and 39. The type 38 was the first indirectly heated output pentode. In a few years, the 6-volt heater took over, and 2.5-volt tubes were discontinued.

Tube developments came so rapidly in 1931 to 1933 that it is impossible to list more than a fraction. Class B amplification was used in the highest-output audio stages [35], [36] and the types 46, 79 and 53 were developed; the latter two types were double triodes, and were the forerunner of a very popular type of tube ten years later. The type 55 and 85 were combination diode-triodes. The 41, 42, 59 and 89 were all indirectly heated screen-grid output tubes. For 110-volt operation ac/dc receivers, with series string heaters, the types 43 and 48 screen-grid output tubes were developed. The year 1932 also saw the introduction of the dome-top bulb and a whole series of new screen-grid RF amplifier tubes [37] in which a separately connected suppressor was used for the first time. This series included the 56 and 76 triodes, and the 57, 58, 77 and 78 RF amplifiers.

About 1933, a considerably more revolutionary tube development took place, one which once and for all consolidated the superheterodyne as the one and only receiver circuit, even in the lowest-cost sets. This was the pentagrid converter, type 2A7 and 6A7, which used electron coupling between an oscillator inner section and an outer, remote cutoff screen-grid mixer section [38]. Thus, in a single tube, high conversion gain was achieved together with freedom from oscillator interaction with the signal circuit. Within a year or two, this converter tube was almost universally used in the U. S., although in Europe a combination triode-hexode was also used in the same general way. From this time on, it became possible to make a 4-tube-plus-rectifier superheterodyne, with performance not too far from 8- and 10-tube receivers of a few years before. For battery portable receivers, a corresponding low drain filament type, the 1A6 was introduced and was used with other 2-volt types in such applications.

In 1935 a change was made in the base and envelope of almost every basic type of receiving tube. The octal base, with up to eight pins, and with a convenient locating lug, became almost a standard from this point in time. A line of octal-base metal-envelope tubes included the 6J5, 6J7, 6K7, 6A8 and 6F6, which were the counterparts of the earlier dome-top bulb line [39]. The electron ray type of tuning indicator tube continued to use glass, of course, and in a year or two there were many straight-sided glass envelope equivalents to the metal types, designated by the suffix GT. Over the years to follow, metal tubes gradually disappeared from use, but the octal base remained.

For a year or two prior to the metal tube, receiver manufacturers had been including from one to three short-wave bands, with frequency ranges up to 20 Mc or even to 60 Mc. This presented problems for the pentagrid converter, and a 5-grid mixer tube, the 6L7, was developed for the metal line [38]. The 6L7 required a separate oscillator, but had much less oscillator-signal circuit interaction at the short wavelengths. A few years later, the 6K8 and 6SA7 converter tubes were devised for the same purpose [38].

During the development of the metal tube, extensive laboratory work had been undertaken to improve the audio output pentode. These endeavors led to an oval cathode, an aligned control-grid and screen-grid to reduce the screen-grid current, and a minimal suppressor consisting of two side "beam-forming plates"; the remaining suppression of secondary emission came from space charge [40]. The first tube using the new beam principles was the 6L6, and within a few years it was followed by a slightly smaller version, the 6V6. These "beam-power" types had higher output, higher efficiency, and lower distortion than the pentode tubes which they largely replaced; the same beam principles are still in use today.

The close of this period of rapid expansion saw receiving tube production rise to nearly 100 million units per year (1936) and price competition, plus mass production techniques, led to cost reductions which were among the most remarkable in the history of the industrial revolution. Whereas the type '01A triode of 1923 had a list price of about $9.00, the five-grid converter tube of 1936 had a list price of only around $1.25. In 1936, about 9 million radio receivers were sold, with a retail value of around 500 million dollars.

Close-Spaced Tubes and VHF, 1936 to 1960

Just as the first period was chacterized by the triode, and the second period by the indirect heater and multigrid tube, the third period is characterized by the use of close grid-cathode spacing. For many years it had been appreciated that closer spacing between control grid and cathode led to higher transconductance. However, tube manufacturers prior to 1936 held firmly to a conviction that 0.015-in (0.4 mm) spacing was about as small as practicable for a low-cost mass-production tube. The improved understanding of transit-time effects [41], fluctuation noise [42], and the principles of wide-band amplification [43] all led to only one conclusion: Practical television and FM at VHF frequencies required that tube spacings be very much smaller.

Fortunately, acorn tube [44] manufacturing experience showed that short lengths of cathode and grid *did* permit reasonable yields, even with 0.005-in spacing. The additional feature of dc inverse feedback, through a cathode bias resistor, turned out to make such spacings practicable even for longer length cathodes, and the first wide-band amplifier tubes, the 1853/6AB7 and the 1852/6AC7 were born [45]. From this point on, almost every subsequent tube development of importance used spacings substantially less than had previously been believed practicable and, most remarkable of all, this was eventually done with very little increase in manufacturing cost. At the same time as this progress was made in receiving tubes, television picture tubes with up to 12-in diameter white screens were developed and the 1939 World's Fair saw the introduction of the first television receivers designed for home use [46]. These operated up to 90 Mc and had IF and video bandwidth of 4 Mc. Just a year before, the first commercial FM receivers [47] were put on sale; they operated in the 50 Mc region.

By 1939, some other chacteristics of future receiving tubes were evident. Metal tubes were getting much competition from glass types, particularly from the GT and a glass base type known as the "loctal." Tube types, essentially the same in principle, but with very minor deviations in basing, or internal capacitances, proliferated almost without end (for this reason, specific tube types will no longer be mentioned in the remainder of this section). A line of miniature glass tubes for battery-operated portable receivers was successfully manufactured [48], and this small sized glass envelope with a new integral 7-pin glass base was destined to become the standard for all except the highest power receiving tubes of the future. The structure was small, inexpensive, and the short leads were ideally suited for

VHF type operation. During World War II, this trend to the miniature glass envelope became consolidated [49], and the tubes which are in use today (1962) in almost every broadcast and TV receiver are essentially World War II types modified for commercial production.

After the war, just about every tube which had been known before the war had a redesigned counterpart in either a miniature, $\frac{3}{4}$-in diameter envelope, a 9-pin $\frac{7}{8}$-in envelope, or in the GT octal-base glass construction. A major change, however, was a greatly increased use of double-triodes in receiver circuitry, particularly in TV receivers. In fact, this type of tube essentially halted the more extensive use of multigrid structures, since it was found that a double triode was a less expensive way to solve a circuit problem than use of two higher-performance multigrid structures [50]. In the case of low-noise TV input amplifiers, the cascode circuit [51] for the double triode actually provided better performance than any known multigrid tube circuit.

In their impact on receivers, the post-war tubes permitted excellent FM performance in the newly assigned 100-Mc band, and television reception up to 216 Mc was most satisfactory. In the television receiver, the special problems of magnetic deflection [52], [53] were solved by special beam type deflection tubes, and low-impedance damping diodes. Picture tube anode voltages were raised to high values permitted by pulse transformers operating filamentary high-voltage rectifiers. The picture tubes themselves were greatly improved, with greater size and aluminized backing for the phosphor [54]. By 1950 it was clear that electronic color television was entirely feasible, at least from a technical point of view, and color-television picture tubes had already been successfully demonstrated [55], [56]. Extensive use of inverse feedback in high-gain audio amplifiers led to greatly improved sound quality, both in receivers and in separate hi-fi equipment.

From 1953 on, tube developments played a diminishing role in broadcast receivers, because of the major impact of the solid-state art, *i.e.*, the transistor and the junction rectifier. The transistor quickly dominated the portable receiver, and the silicon rectifier is rapidly replacing the vacuum tube types in ac receivers. By 1956, tube developments were already altering to match the transistor. In the automobile receiver, an old principle, the space-charge grid (invented in 1913, but never used), was revived, so that 12-volt operation became feasible in the so-called "hybrid" receiver, with tubes for the RF and IF and a tube driver for a transistor audio output [57]. A radically new line of tubes, called Nuvistors, was developed [58]. These were very small in size, had extremely low power consumption, and had superior high-frequency performance over other low-cost tubes and transistors [59].

At the close of this period, receiving tube sales were still high[3] because the transistor had not yet entered the TV or FM receiver, and low-frequency broadcast receiver sales were chiefly confined to portable and auto receivers. However, the trend is clear and the amplifying type of receiving tube, as we knew it in the past, has clearly seen its zenith.

[3] In 1959, over 400 million receiving tubes were sold.

The Present and the Future

At the present time, the major advantages which the receiving tubes have over the competing solid-state devices are cost and performance. The tube has had forty years of improving technology, mass production, and cost reduction, while solid-state devices have had only about ten years. If size and power consumption are disregarded, there is almost no function in which the receiving tube is not superior in performance to the semiconductor device, except perhaps for the power rectifier. Nevertheless, it is also clear that the receiving tube is at a time of minor refinements, and no major new inventions are likely. The solid-state device, on the other hand, is only just beginning to achieve low-cost production, and major performance-improving inventions are being made each year.

Perhaps the real clue to the future lies in integrated and functional electronics, or microelectronics as it is also called. Future receivers will surely include functional subsystems, replacing the arrays of active and passive components we now use. By far the greatest research effort in micro-electronics is going on in the solid-state area. However, there are several groups of competent investigators who are convinced that a form of vacuum-tube technology may yet be the answer. The outcome will probably lie in both areas, *i.e.*, there will be microelectronic systems of both types. Nevertheless, in the writer's opinion, the broadcast and TV receivers of the future will slowly and inevitably tend toward predominant use of solid-state devices, with the exception of the picture tube.

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