RB-86

GAS DISCHARGES AS TECHNICAL DEVICES

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Gas discharge devices are extremely versatile because their operation, in distinction to that of vacuum tubes, involves mobile positive charges as well as electrons. This allows them to operate efficiently as switches, light sources, and as many other miscellaneous types of devices. In many fundamental respects their operation is similar to that of semiconductor devices. The basic properties, limitations, and advantages of gas discharge devices will be discussed with particular reference to the increasing competition from semiconductor devices.

Introduction

There are a great variety of gas discharge devices in use. These are of all sizes, characteristics, power and current handling capabilities, and depend upon a complicated assortment of phenomena for their operation. Indeed, the details of the operation of some of these devices are so complicated that they still defy explanation. While an empirical understanding of device operation sufficed in the past, constantly increasing demands on performance have forced the manufacturer to put his understanding upon a more concrete, atomic, basis. There is also an increasing realization that improved knowledge, obtainable only by basic research, will lead to the invention of new types of devices. Since 1945 there has been a considerable increase in the research effort on gas discharge devices in industrial concerns as well as in universities. This has been aided by greatly improved microwave and high speed oscilloscope methods that were developed during the war.

Gas discharge devices are intrinsically more complicated than vacuum tubes because one is concerned, not only with mobile electrons, but also with mobile positive and negative ions and also with mobile neutral particles. On this account it is not surprising that the understanding of gas discharge devices has lagged behind that of vacuum tubes, and that gas discharge devices are more versatile and find use in so many widely different applications.

Gas discharge devices might be broadly classified as:

1) Switches and control devices.

2) Light sources.

3) Miscellaneous, including, for example, particle counters, voltage regulators, and noise sources.

In the first category one finds thyratrons, rectifiers, cold cathode trigger tubes, and microwave (TR and ATR) switch tubes. Of the order of a million such units are sold in this country each year. In the second category are fluorescent tubes, mercury arc tubes, sodium vapor lamps, carbon arcs, and an assortment of other types of lamps, including the ubiquitous neon sign, too numerous to list here. Upwards of 200 million units in this category are sold each year. Voltage regulators, amounting to about a million units per year, make up the largest portion of the miscellaneous category. The remaining portion is composed of rather specialized devices, that while important, are of limited commercial interest.

While not in the "device" classification gas discharges are widely used for producing high temperatures in metal cutting and welding,[1] and find ever-expanding use in certain chemical reacrions.[2] The latter application seems to have enormous potentialities.

Gas discharge devices should not be dropped into a compartment by themselves. They depend upon atomic and electronic processes just as do solid state, liquid, and vacuum devices and hence are intimately related. Furthermore, regardless of the medium with which a device is normally associated, close inspection often reveals that operation depends upon the cooperation of two or more different states of matter. A thyratron, for example, uses the gaseous state in its interelectrode space but heavily depends upon solid state phenomena at its electrodes, in particular at the cathode. A transistor, while classified as a solid state device, often depends critically upon the gaseous ambient in which it is operated. For these and utilitarian reasons frequent comparisons between gaseous, solid state, and vacuum devices will be made here. These will help, perhaps, in predicting the extent to which semiconductor devices will supplant gas discharge devices in the future.[3]

The following treatment will be primarily aimed at describing how the fundamental gas discharge processes are utilized in practical devices. Basic limitations will be pointed out. Detailed description of device construction and attendant circuitry will be minimized unless it is pertinent to the basic operation.

This discussion will start with gas discharges as switches and control devices. These will, in one way or another, involve almost all the basic gas discharge phenomena and will lead in a natural way to a consideration of the other applications listed above.

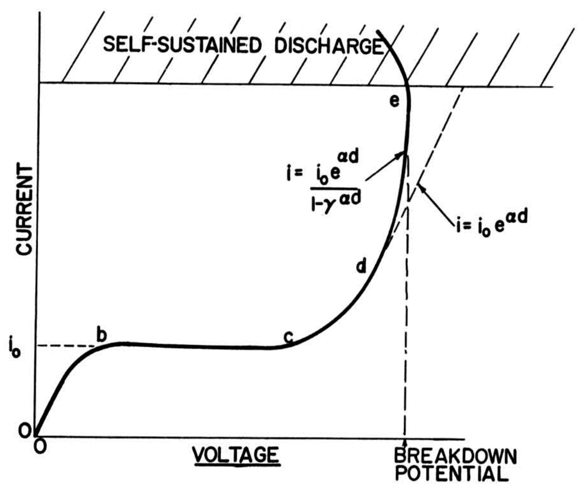

Fig. 1 – Prebreakdown cold cathode current-voltage characteristic.

Switches and Control Devices

Non-Conduction State

An ideal switch would have an infinite impedance when open, regardless of the applied potential; it would have a zero impedance when closed, regardless of the current. In addition, it would close and open instantaneously with a minimum of driving power, have an infinitely long life, have stable characteristics, generate no undesirable side effects, be as small as possible in weight and size, be insensitive to its ambient, and require a minimum of auxiliary power supplies and circuitry. The producer hopes for simplicity in manufacture and the customer demands a low price. To be sure, the devices in use today fall far short of the ideal. However, the stringent requirements listed above are useful in evaluating switch and control device performance and will set the mood for discussion to follow.

Up to high electrical potentials a gaseous dielectric between two electrodes would normally have a very high impedance. A typical current-voltage relationship between two electrodes separated by gas has the form[4] shown in Fig. 1. The current in the region obc results from cosmic and natural radiation. This current has a value approximately of the order of 10^{-16} amperes, or less, so that the d-c impedance might be of the order of 10^{18} ohms. With electrodes of low work function (≈ 1 volt) thermionic emission and photo electron emission from background light could result in much larger currents and, ultimately, decreased breakdown potentials. For these reasons steps are taken in high voltage devices to prevent critical electrodes from: (1) developing unduly low work functions, (2) becoming overheated, and (3) exposure to light. The first objective is approached by the use of shielding to prevent deposition of low work function material (such as from an oxide cathode) and also by the use of a special electrode material,[5] such as carbon or gold. The engineer hopes for a solution to the second objective by careful location of electrodes (especially with respect to a hot cathode), heat shielding, and adequate cooling.[6] The third item can cause difficulty in Geiger counters and certain types of trigger tubes. A solution is usually found by using an opaque tube envelope.

Thermal ionization of the gas, as described by Saha equation, is not normally a problem. In a transistor, however, thermal ionization is the main generator of the charge carriers. This follows because the effective ionization potential of atoms in a typical semiconductor lies between about 10^{-2} and 1.5 volts whereas it is tens of volts in a gas. This fact can be of enormous advantage at room temperature, but puts a basic limitation on semiconductor operation at elevated temperatures.

In the region cd of Fig. 1 the electron current increases according to the familiar Townsend avalanche relation

$$i = i_0 \epsilon^{\alpha d} \tag{1}$$

where i is the anode electron current, i_0 is the cathode electron current, d is the cathode-anode spacing, and α is the first Townsend differential ionization coefficient which describes the number of ion-electron pairs produced by impact ionization per electron per centimeter of electron path. This coefficient is a strong function of the gas parameters and the electrode potentials. Beyond point d on the curve the ionization products, ions and radiation, provide an appreciable feedback term by generating new electrons at the cathode. The total current than takes the form[7]

$$i = \frac{i_0 \epsilon^{\alpha d}}{1 - \gamma \epsilon^{\alpha d}} , \tag{2}$$

where γ is Townsend's second coefficient. It accounts for the new, secondary, electrons generated, both at the

the cathode and in the gas. This second coefficient is mainly a function of the cathode material and the gas parameters. Instability leading to breakdown occurs when the denominator of Eq. (2) goes to zero. It is interesting to note that this feedback effect is very appreciable in a gaseous medium, but is not necessarily so in a solid state device. Practically speaking, this means that gas discharge devices are tricky to handle in the region about *d* of the curve while certain semiconductor devices* can operate well into the avalanche region without special means of stabilization.

The curve in Fig. 1 corresponds to one particular gas pressure. The relationship between breakdown voltage and the product of electrode spacing and gas pressure is given by the familiar Paschen curve shown in Fig. 2. To the left of the curve minimum the breakdown potential is high because a cathode electron strikes very few atoms on its way to the anode. To the right of the minimum there are so many atoms that a cathode electron has difficulty in picking up ionizing energy in the electric field before it loses its energy in a collision with a neutral. It is apparent that a given breakdown potential can be attained at two different abscissae, one on each side of the curve minimum. Generally, in devices having a copious electron emission from the cathode (hot cathode devices such as the thyratron) one chooses to operate to the left of the Paschen minimum. As shown later, this tends to maximize switching speed. Cold cathode devices, which depend upon the discharge itself for cathode emission, require relatively high gas pressures and necessarily operate to the right of the minimum.

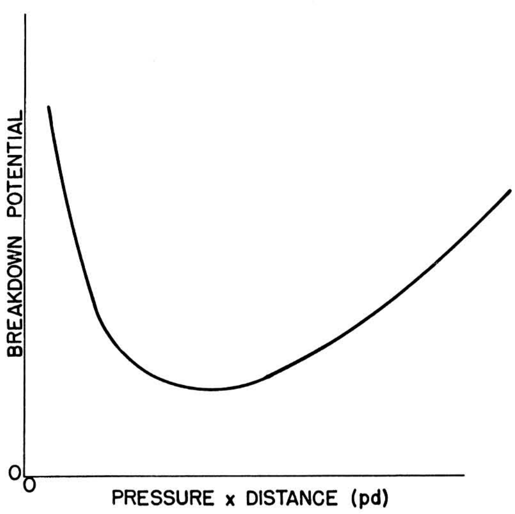

Fig. 2 – Paschen curve.

A decrease in cathode work function tends to displace the Paschen curve downwards. Deposition of a low work function material, such as barium, from the hot oxide cathode in a thyratron is inhibited by using as low a cathode temperature as practicable in addition to the means previously mentioned. Added to the spurious kinds of emission already mentioned is field emission. This is minimized by the careful elimination of sharp points and corners on sensitive electrodes. The treatment,[8] called "spot knocking", is frequently used during the processing of a tube. This calls for the application of substantial overvoltages to the cold, evacuated tube in order to induce field emission from any local sharp points and burrs produced during fabrication. The high local current density, characteristic of field emission, plus ion bombardment, rapidly destroys these field emission centers. The Malter effect,[9] which is a spurious high field emission arising from specks of insulating material on the negative electrode, has been a source of erratic breakdowns in mercury arc rectifiers.[10] In some cases, spurious breakdowns between electrode leads, both inside and outside the device, are troublesome.

In Table I are listed the commercial ratings relative to the voltage handling capabilities of several representative gas discharge devices. The ratings of several vacuum and semiconductor devices are included for comparison. It is to be noted that the gas discharge devices (all hot cathode) have pd products that are rather small compared to the Paschen minimum value, which usually lies between 1 and 10. The breakdown potential obtained from Paschen curves and listed in the last column are only approximate values because of (1) the extrapolations necessitated by the paucity of information in the literature on small pd values, and (2) a somewhat different electrode material and geometry from that referred to in the Paschen curves. There is little doubt, however, that the rated maximum anode potentials usually are well below the Paschen breakdown values. Part of this difference arises from the usual commercial safety factor and part from the spurious effects discussed earlier.

The gas discharge and vacuum devices are seen to operate with a minimum rated field well below the 10^7 volts necessary for field emission. In addition to field emission the vacuum devices are limited by transient gas discharges caused by the sudden and unpredictable release of gas from the electrodes.[8] Although the solid state devices have a low maximum operating voltage, they have very high internal electric fields because of their small dimensions. There are three mechanisms which can limit the breakdown field in semiconductor devices. These are: (1) Zener breakdown,[11] which is field induced ionization across the forbidden gap; (2) avalanche breakdown[12] of a sort similar to that found in gases; and (3) surface breakdown[13] which is erratic and not yet well understood. The first and second mechanisms occur at roughly 10^5 volts per centimeter in germanium and silicon. The third mechanism usually sets in at lower fields.

Some of the devices listed in the table are shown

*For example, a back-biased germanium junction diode.

in the photograph of Fig. 3. Reading from left to right are: the type 2050, 2D21, and 884 gas tubes; the type 8013A vacuum tube, and the type 1N93 germanium diode.

Conduction State

Next is the problem of keeping the impedance zero, or at least very low, during switch closure. We immediately thick of ionizing the gas. If this can be done at a rate of G ion-electron pairs per second per cubic centimeter there will be an equilbrium concentration of N carriers, where

$$N = G\tau \tag{3}$$

for the case where the mean carrier lifetime is τ seconds. If the mobility of the electrons* is μ cm/sec per volt/cm, the ionized gas, or plasma, will have a conductivity

$$\sigma = eN\mu . \tag{4}$$

*The ion mobility is approximately 10^3 times less so that the ionic contribution to conductivity need not be considered.

Inserting the typical values, $N = 5 \times 10^{10}$ and $\mu = 5 \times 10^6$, for a small thyratron, such as the 2050 listed in Table I, the conductivity is found to be 0.04 mhos per cm, a value comparable with that of germanium. The ionized path has a length of about 0.3 cm so that a resistance of about 8 ohms would be expected. This is not far from the observed value. The problem, however, is far more complicated than indicated by the simple considerations listed above. In addition to the plasma resistance there are resistances associated with high field layers, or sheaths* , that exist adjacent to electrodes[14] and also in the interelectrode space.[15]

The simple picture portrayed above lacks a most important ingredient, the cathode. If the electrons carry current into the anode, how does one get electrons out of the cathode electrode to maintain current continuity? This turns out to be perhaps the roughest problem that confronts the electron tube engineer. Cathodes of the sort known today usually are the most important limiting factor, directly or indirectly, in device performance.[16] They are often troublesome to make and control, change with life, and usually are the major limitation on device life. As is common with boundaries between two phases of matter,

*In solid state parlance these layers are known as "depletion layers".

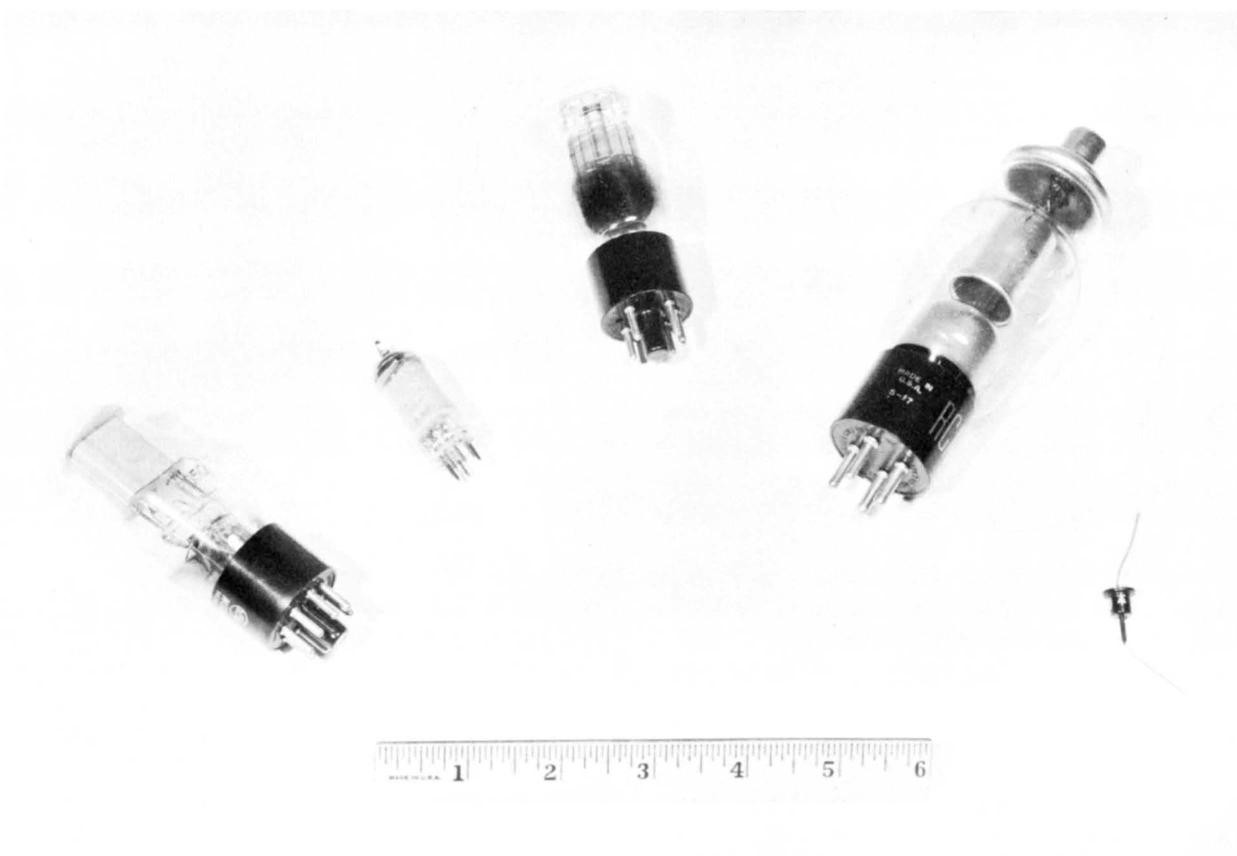

Fig. 3 – Small thyratrons, a high voltage vacuum tube rectifier, and a germanium diode.

TABLE I

Tube Type		Interelectrode Medium Type	Pressure(p)	Approx. Size Length[1]	Dia.	Max. Rated Anode Potential (V_c) Forward	(V_i) Inverse	Approx.[2] Electrode Spacing(d)	Approx. Max. Field[3] (E_f) Forward	(E_i) Inverse	Press. Spacing Product pd	Paschen Breakdown Potential
			(mm)	(cm)		(volts)		(cm)	(volts/cm)		(mm)(cm)	(volts)
2050	thyratron	xenon	~ 0.2	10	3	650	1300	0.3	2170	4300	0.06	> 10,000
884	"	argon	"	10	3	350	350	0.2	1750		0.04	> 10,000
4C35	"	hydrogen	0.5	13	6	8000	-	0.15	53,000	-	.075	~ 30,000
857B	rectifier	mercury	0.0084[4]	50	18	-	22,000	1.9	-	11,500	.015	100,000[5]
8013A	"	vap.vacuum	-	15.5	5.5	-	40,000	1.0	-	40,000	-	-
1N93	"	germanium	-	0.7	0.7	-	300	-		~ 10^5	-	-

[1]Includes base

[2]Anode to nearest oppositely polarized electrode

[3]$E_f = \frac{V_c}{d}$ $E_i = \frac{V_i}{d}$

[4]40°C

[5]L. G. Guseva and B. N. Klarfeld, *Zh. Tekh. Fiz.*, **24**, 1168, 1954.

here solid and gas, there is a great sensitivity to very small amounts of impurities that might be introduced either during fabrication or during operation. In a gas discharge device there is the added complexity caused by bombardment of the cathode by ions, and also by neutral particles that have been knocked loose, or sputtered, from other electrodes. Cathode problems are largely avoided in a semiconductor device, like the transistor, because the entire conduction process is carried out wholly within one medium.

The deleterious effects, mechanical erosion and gas cleanup, that stem from ion bombardment of the electrodes deserve special comment because they are of great importance in limiting device life and performance. Mechanical erosion (sputtering) is a function of the ion mass and energy, the angle of incidence, and the mechanical properties of the material used as a target. Removal of a surface atom from the target occurs when the energy imparted to it by an incoming ion is sufficient to break its bonds with adjacent atoms. The sputtering threshold voltage V_0 for ions at normal incidence to a single crystal target is given by the empirical relation[17]

$$V_0 = \left[\frac{1.7 \times 10^5 (M_g + M_n)\phi^2}{M_g^{1/2} M_m V_s} \right] , \qquad (5)$$

where M_g is the atomic weight of the gas ion, M_m is the atomic weight of the target atoms, V_s is the bulk sound velocity in the target in cm/sec, and ϕ is the heat of sublimation of the target in kcal/mole. This agrees with observation in predicting a threshold of 90 volts for mercury ions striking a nickel target. It has been found also that atoms are removed at much lower energies when the ions arrive at oblique incidence.[17] Particularly susceptible to removal are atoms at grain boundaries, corners, and mechanical imperfections. The sputtering yield measured in number of atoms removed per incident ion is a rather erratic function of the target surface conditions. It is very roughly of the order of 10^{-3} times the voltage by which the ion exceeds the threshold value givenin equation (5). Thus, it is to be expected that an ion current density of one ma per cm^2 arriving on a piece of nickel with 100 volts in excess of the threshold will remove an atomic layer roughly every ten seconds. Gas clean up occurs when ions are driven into the target surface or are carried along, with sputtered atoms to be buried on some other surface. This process has not yet been extensively studied. Small light ions such as helium and hydrogen appear to clean up more rapidly than heavier ones. A very crude estimate might be made from the fact that one helium ion out of a thousand disappears when a tungsten target is struck with 200 volt ions.[18] This increases by almost an order or magnitude for every 100 volts increase in energy. Tracer techniques indicate that the cleanup process is strongly influenced by grain boundaries and mechanical defects on metal surfaces.[19] Gas cleanup effects are lessened by presaturation of the tube parts with gas and also by providing gas reservoirs as is done with the larger sizes of hydrogen thyratrons. The destructive potential of both sputtering and cleanup make it imperative to design[20] and operate gas discharge devices to minimize the possibility that high electrode voltages are present[21] when the gas is ionized. Solid state devices have a considerable advantage in having all their massive charged particles securely locked in place in the crystal lattice.

The possible phenomena that may be employed to provide cathode emission are: photo emission, field emission, thermionic emission, and secondary emission. The engineer must make a choice according to his requirements. All of these phenomena are used in practical electron tube devices, and all have certain advantages and disadvantages. The first supplies too low a current density to be practical and so need not be mentioned further. It does, however, supply a fraction of the total emission delivered by secondary emission. Field emission can deliver enormous current densities. It is thought to be the source of the emission in mercury arc tubes where, it is believed, the density might be as high as 10^6 amperes per cm^2[22]. This type of emission requires fields of the order of 10^7 volts per cm for materials with several volts of work function. This severely limits the applicability of the phenomenon to very specialized conditions, such as in the mercury pool tubes, where it occurs automatically for reasons as yet unknown.[23]

Thermionic emission, as used in thyratrons and other externally heated hot cathode tubes, yields a dc current density up to about one half ampere per cm^2[24]. It has the disadvantage of requiring an auxiliary energy source for heating the cathode. When no particular efforts are made to reduce heat loss, about 15 watts of heating power per dc ampere of emission are required. This power disappears by a combination of radiation, conduction through leads, and convection or conduction through the gas. The latter is generally not important unless high gas pressures and gases of low atomic or molecular weight are used. For example, with xenon at one millimeter pressure the total heat loss is roughly ten per cent greater than the case where the cathode operates in a vacuum.[25] Hydrogen at one millimeter of pressure would cause an appreciably greater heat loss because the gas conduction loss varies inversely as the square root of the gas molecular weight. These considerations are only of first importance in cases where overall efficiency is of paramount interest. Extensive heat shielding, such as found on larger size tubes can reduce the heat loss to as low as two watts per dc ampere.[6] Vacuum tubes cannot take advantage of such

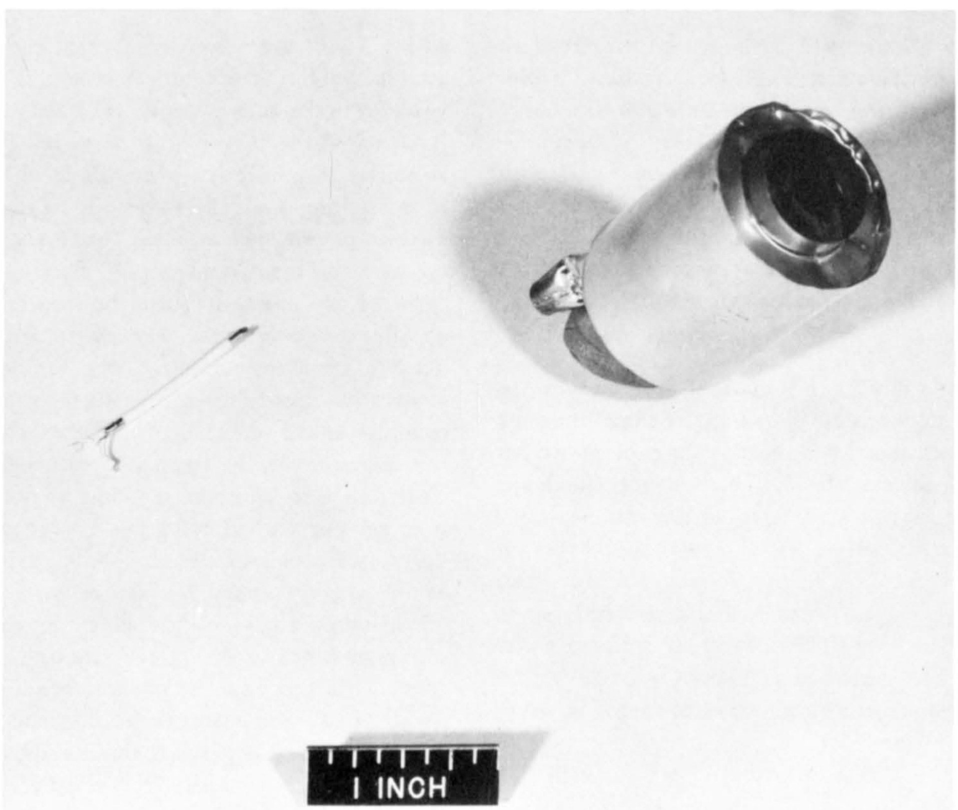

Fig. 4 – Thyratron cathodes. A small unshielded one and one with heat shielding for larger size tubes.

heat shielding because of the additional space charge limitation of the anode current that would be introduced by the tortuous conduction paths inherent in the geometry of any practical heat shielding scheme.

In Fig. 4 are shown photographs of typical externally heated cathodes. On the left is an oxide coated cathode of the sort used in small gas tubes. It has a square centimeter of emitting area, is rated for 0.100 amperes of dc emission, and requires about 3.6 watts to heat to its operating temperature of about 850°C. It uses no heat shielding. It is composed of a nickel sleeve of relatively pure nickel because certain impurities, such as silicon, cause an electrical resistance to develope between the sleeve and the oxide coating if the tube remains in a standby condition. The oxide coating is applied as a mixture of barium, calcium, and strontium carbonates. It should be noted at this point that the fabrication and processing of oxide cathodes is an art rather than a science.[26] The emission mechanism, itself, is still somewhat of a mystery. More recent theories treat it as a semiconductor phenomenon.[27] The cathode on the right is of the sort used in larger size thyratrons. The emitting surface is on the inside of the cylinder and the surrounding heat shielding enables the cathode to deliver 2.5 amperes of emission for about 10 watts of heater power.

The use of thermionic emission from oxide cathodes restricts the gas filling to the noble gases, mercury and hydrogen; most of the other gases are highly injurious to such cathodes. This is not surprising because a high electron emission capability implies great capability as a chemical reducing agent. The noble gases and mercury are, in fact, preferable for most devices because they are easy to handle and reduce the likelihood of troublesome chemical reactions with other parts of the device structure.

The high pressure arc discharge automatically releases enough energy to heat its cathode electrode to the point of copious electron emission without any need for an external heating source. In fact, the gas temperature becomes so high that there is difficulty in preventing the anode from becoming an emitter if the electrode potentials are suddenly reversed. A scheme[28] has been devised to get around this difficulty, but the device is not a particularly attractive one because of very low overall efficiency.

Thermionic emission when produced by an independent energy source is independent of discharge conditions and so gives a wide latitude in the choice of gas pressure. In particular, low gas pressures can be used and, as will be shown, these lead to rapid switching. Furthermore, the copious and readily available electron supply furnished by such a cathode permits the switching of large amounts of power by much smaller powers. This important characteristic is one of the cardinal virtues of the thyratron.[6] The basic structure of this device is sketched in Fig. 5a. The potential distribution along the path x-x for the pre-conduction state with a negative grid potential and a

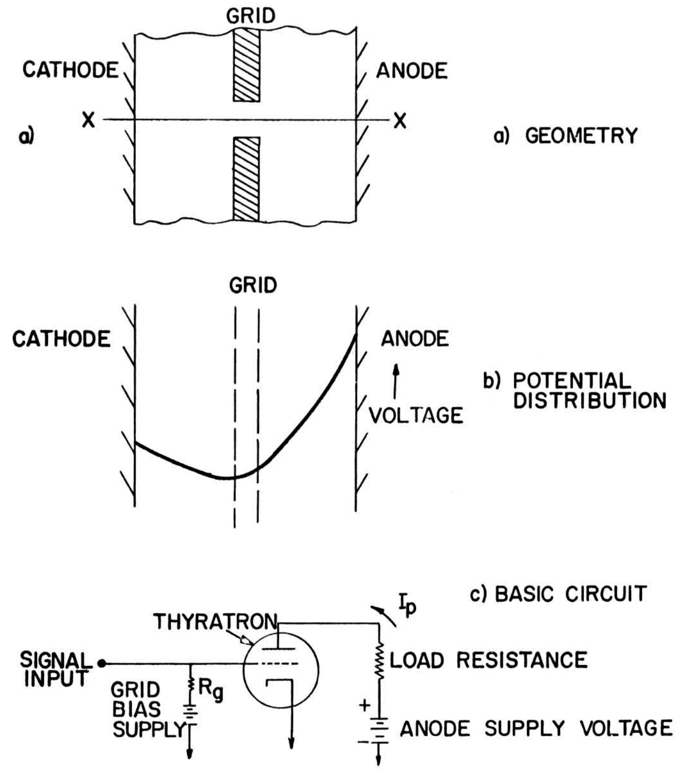

Fig. 5 – Thyratron geometry, potential distribution, and basic circuit.

positive anode potential is shown in Fig. 5b, and the essential circuitry in 5c. The cathode electrons are prevented from reaching the anode by the potential barrier set up by the negative grid. This barrier can be lowered by a reduction in the grid bias by an input signal to the point where a few electrons can climb over, by virtue of their thermal energies. These electrons will then rapidly pick up energy in the anode field. The positive ions that are generated in the grid-anode space by these electrons will fall back into the cathode-grid region, raise its potential slightly, and so allow more electrons to escape. The process builds up very rapidly and is consummated by a complete breakdown in times of the order of a microsecond.[29] The steady state anode current I_p is then principally limited by the load resistance. If the firing and conduction process is carried out on an ac basis it becomes possible to define a power gain for the device.[3] This is the ratio of the power developed in the load to the signal driving power. The former power is roughly equal to the product of the maximum allowable current and forward voltage. This current is mostly a function of cathode size and allowable power dissipation in the tube. The voltage has been discussed previously. The approximate grid signal driving power is obtained from the power dissipated in the grid resistor R_g. The value of R_g can be made rather large ($\approx 10^5$ ohms), but has a limiting value set by the grid currents which occur during the cycle of operation, in particular during the deionization period following conduction.[30] The signal voltage required to override the bias and fire the tube has a value set by the relative effect of the anode and grid electrodes in influencing the electric field in the cathode region. This is an electrostatic problem set by tube geometry the same as the amplification factor of a vacuum tube. A typical curve indicating the relative effect of the grid and anode in controlling the field near the cathode, and hence breakdown, is shown in Fig. 6. The tube remains unfired in the region below the curve and fires immediately if the curve is crossed. The power gain obtained in the manner sketched above might be as high as 80 db* for a small thyratron. This simple analysis brings out the essential physics and practical aspects of thyratron power gain but is not exact because it neglects wave shapes, the effect of the grid impedance on the input circuit, and other factors mostly having to do with the recovery of the tube of its prebreakdown characteristics.[30] It is obviously not possible to attain such high power gains if the grid, or whatever sort of electrode might be used in a device, has to do work in creating the supply of the principle charge carriers. This is the case, for example, with the cold cathode trigger tubes to be described. These commonly have a 10-30 db maximum power gain. The trigger electrode has to initiate the electron avalanche to the anode by itself taking part in a discharge which expends considerable energy in forcing electrons out of the cathode. On the other hand, both transistors[31] and vacuum tubes are similar to the thyratron in that a copious carrier supply is always available and ready to flow when the control electrode lowers a potential barrier. Junction transistors commonly have a power gain in the 40-50 db range. Depending on the grid leakage currents, vacuum tubes can have 100 db or greater power gain close to zero frequency.

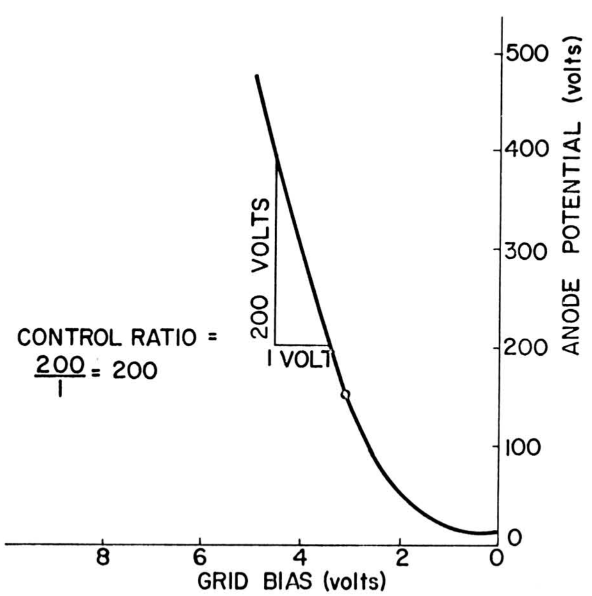

Fig. 6 – Thyratron control characteristics.

*Power gain (db) = 10 $\log_{10} \frac{\text{Output power}}{\text{Input power}}$

The power gain and general operating characteristics of a thyratron can be improved by introducing a third, or shielding, electrode to isolate partially the grid from the cathode and anode.[32] As pointed out previously, this helps the voltage breakdown characteristics by reducing spurious grid emission. In addition (1) the grid circuit has better isolation from the electrostatic influence of the anode circuit, (2) the grid area can be reduced with a corresponding reduction in the ion current flowing to the grid during the conduction and the post conduction periods.

The last important form of cathode emission to be considered is secondary emission. In the sense used here, this means the release of electrons from a cathode by a combination of ion bombardment, action of metastable atoms, and photoemission resulting from photons generated by the discharge process in the gas.[33] Secondary emission processes are utilized in almost all cold cathode tubes, the mercury pool tubes apparently being about the only exception. Typical cold cathode tubes employing secondary emission are the trigger tube, shown on the left in Fig. 7, and the voltage regulator tube shown on the right. Secondary emission tubes[34] are normally designed to operate with the normal glow discharge so that the cathode current density is limited to a few milliamperes per cm^2. Higher current densities lead to operation in the abnormal mode wherein there is usually severe cathode deterioration from the increased ion energies. The main potential drop in the tube is located adjacent to the cathode and has a value ranging from 50 to about 200 volts depending upon the gas pressure, type of gas, and the cathode material. A minimum of about 50 volts is required for the secondary emission process to be self-sustaining. This means that the usual cold cathode device is limited to a resistance of the order of $50/10^{-3}$ = 50,000 ohms per cm^2 of cathode surface. The minimum operating pressure is mainly determined by the cathode current density desired, since both theory and observation show that the available cathode current density j is determined by the gas pressure p according to the relation[35]

$$j = (constant)\ p^2. \tag{6}$$

The upper pressure limit is more nebulous to define. The deionization rate, which is a pressure dependent diffusion phenomenon, gets slower for increasing pressure for given tube dimensions. If the tube dimensions are decreased to compensate for this, then engineering difficulties attendant upon the attainment of small dimensions arise. Decrease in size can also lead to power dissipation difficulties which might manifest themselves by decrease in life and stability of operating characteristics. High pressures increase the tendency for a glow-to-arc transition,[36] particularly during higher than normal transient currents. This phenomenon would cause cathode damage. The above considerations lead to an engineering compro-

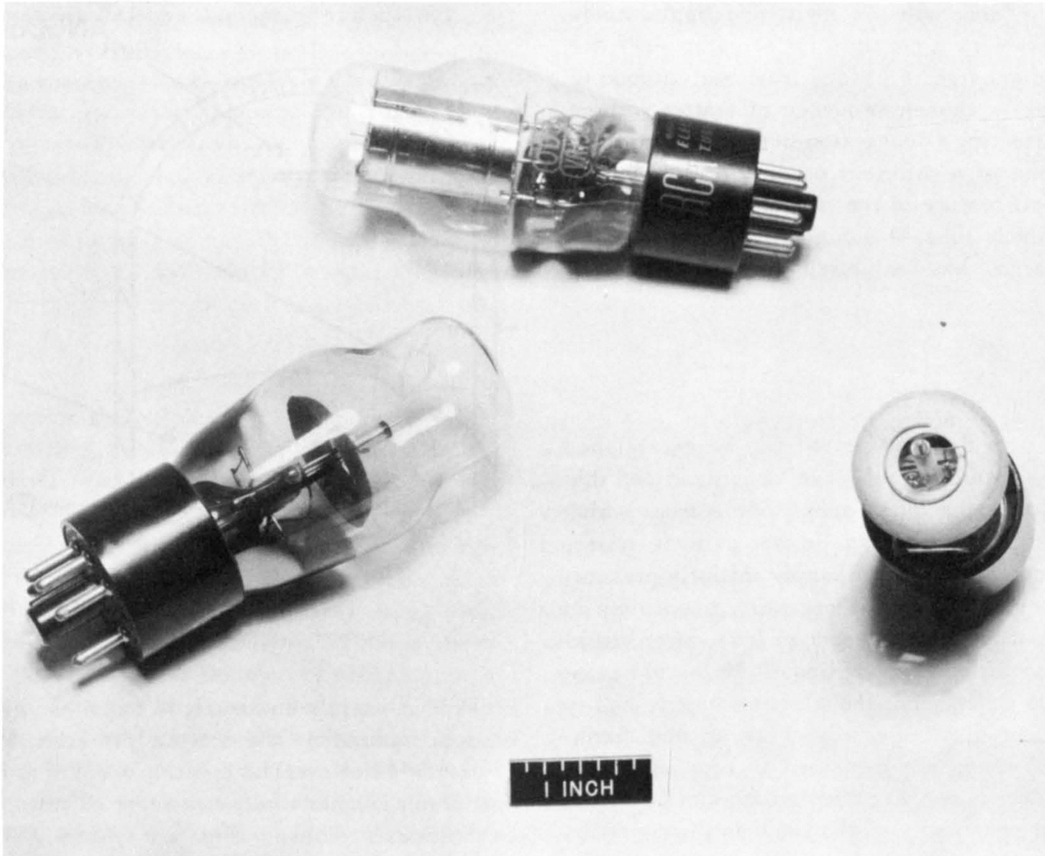

Fig. 7 – Cold cathode tubes. Trigger tube, voltage regulator tube, and trigger tube electrode structure.

mise at a pressure of noble gas in the range of tens of millimeters as exemplified by the filling in the tubes shown in Fig. 7.

The type OA4-G cold cathode trigger tube shown at the left in Fig. 7 has its internal construction illustrated by the disassembled tube on the right. The cathode is the disk-like structure. The anode is the wire projecting beyond the end of the glass tubing. The cathode surface is larger than that of the anode because of the cathode current density limitations. The trigger electrode is the small wire positioned across the cathode face at a distance of about 0.1 cm from the cathode surface. The tube has the salient characteristics shown in Table II.[37] With less than the peak break-voltage, say 140 volts, applied to the anode the tube is non-conducting. When 90 volts are applied to the starter it will break down. If this breakdown current is allowed to be at least as high as 100 μa the anode-cathode gap will break down. If the anode load resistance is of a value that will allow 100 ma to flow to the anode, the power developed across the load resistor will be $0.1 \times (140 - 70) = 7$ watts. The input power necessary to do this is approximately $90 \times (100 \times 10^{-6}) = 9 \times 10^{-3}$ watts. The power gain is thus of tne order of 10^3, or 30 db. The input power is less than the output power because: (1) the pressure-distance product of the starter-cathode is less than that of the anode-cathode, allowing breakdown to occur at lower applied potentials; (2) the current involved in the starter breakdown can be less than that in the main gap because a relatively small amount of ionization placed in the main gap by the starter breakdown will be amplified by the usual avalanche effects to produce breakdown to the anode, the final value of anode current being limited only by cathode capabilities or by the load resistance. The OD3 voltage regulator tube shown at the top of the photograph will be discussed later.

TABLE II

Peak anode breakdown potential	225 volts
Peak starter breakdown potential	90 volts
Starter current required to transfer discharge to anode for 140 volt anode potential	100 μa
Anode conduction drop	70 volts
Maximum anode current	100 ma
Average anode current	25 ma

For counting and multiple switching applications cold cathode tubes with a multiplicity of cathodes[38] are often used. The discharge is passed from one cathode to another by a properly chosen sequence of starter voltage pulses, thereby affecting a connection between the common anode and any one of *n* different other circuits. In distinction to the on-off feature of the trigger tubes described above, a cold cathode tube,[39] using certain properties of a corona discharge, has exhibited continuous control operation.

Switching Speed

The speed at which conduction can be established involves the rate at which the gas can be ionized and this depends strongly upon the initial supply of electrons which are present to start the process. In hot cathode tubes, where there is a copious electron supply initially present, conduction ensues under normal operating conditions in times of the order of one microsecond, or less, after breakdown initiating conditions are applied.[29,40] In cold cathode tubes, on the other hand, the electron supply has to be generated as the discharge progresses so that breakdown (ionization) times are measured in tens of microseconds.[39] The user of a cold cathode tube can be inconvenienced by the sensitivity of the breakdown properties of these tubes to the magnitude of the initial electron supply as affected by ambient light and radioactivity.[34] In fact, the cold cathode tube breakdown time can be used as a measure of the number of electrons which initiated the process.[41] Generally, for both hot and cold cathode tubes the breakdown times are decreased by the use of high initiating potentials and small tube dimensions.

The constancy of the breakdown time is sometimes as important as its total length. This is particularly true of radar modulator applications where the maximum allowable statistical fluctuation of the pulsing operation can be of the order of millimicroseconds.[40] The statistical fluctuations in the breakdown time of a discharge have to do with the probability that the primary electrons will be multiplied by an avalanche process. Since this probability is directly proportional to the number of the primary electrons, hot cathode tubes, such as the thyratron, are the natural choice for obtaining a minimum of fluctuation in the breakdown time.

A decrease in the starting time of an ignitron, which is a cold cathode tube that operates with field emission from a mercury pool, is costly in terms of starting power. Conduction in an ignitron, whose essential construction is shown in Fig. 8, is started by applying a current pulse to the starter. The latter is a high resistance rod dipping into the mercury. The discharge is believed to start from field emission taking place in the region near the junction of the starter and the mercury surface.[42] The spots of field emission transfer their current to the anode and

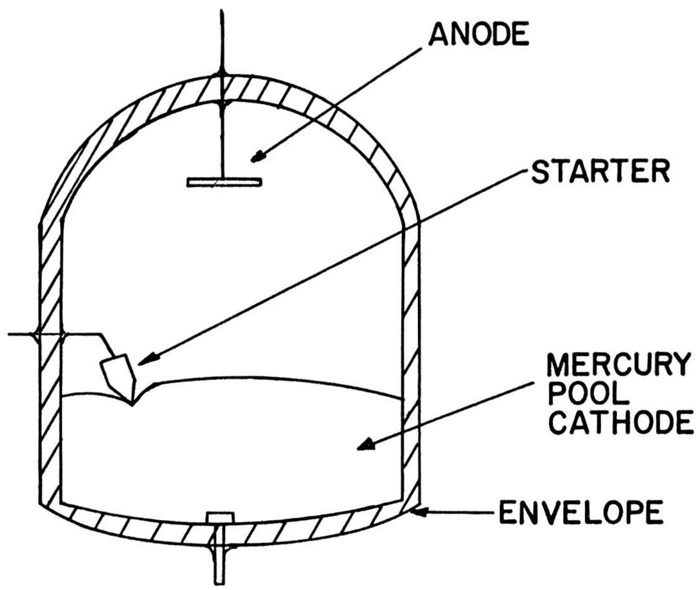

Fig. 8 – Ignitron construction.

breakdown rapidly ensues. It is found empirically that the energy required by the starter, per start, is roughly one joule.[43,44] However, for ignition to occur it is also necessary that a certain minimum current or voltage be supplied to the starter. These values are typically 30 amperes and 200 volts.[43] Therefore, the decrease in starting time required for higher frequency operation must be obtained at the expense of higher driving power. This, however, is independent of the power handling capabilities of the device so that it is advantageous to use the ignitron principle in large tubes. Attempts to reduce the driving power requirements of mercury pool tubes by other types of starters have been hampered by the wetting properties of mercury and mechanical erosion of the starting elements by ion bombardment.[44] The statistical fluctuations in breakdown times of mercury pool tubes are particularly bad only partially as a result of the mechanical motion of the mercury surface.[45]

Before discussing deionization (recovery) times of gas discharge devices it is helpful to consider certain properties of the ionized gas that are present during conduction. In any gas discharge device with appreciable conductivity the ionized gas forms a plasma, a region of high but equal densities of free electrons and positive ions. As in a metallic conductor the electric fields in the plasma are very small and tend to remain small even when large externally applied fields are present. The plasma insulates itself from external fields by forming thin surface layers, called sheaths, that contain sufficient space charge to terminate the electrostatic flux originating from the exterior. This behavior is not different from that of a metal or a semiconductor. Surface space charge regions, shielding the interior from chemically acquired surface charge, are particularly in evidence in semiconductors, for example.[46] Here a large part of the surface space charge is composed of fixed donor or acceptor charge. In a gaseous plasma the space charge is composed of moving charges enroute to the field producing electrode. The thickness d in cm of this space charge region is related to the electrode-plasma voltage by the familiar 3/2 power law

$$d^2 = \frac{2.33 \times 10^{-6}\, V^{3/2}}{J\sqrt{M/m}} \qquad (7)$$

where J is the particle current density in amperes per cm^2 diffusing into a planar sheath from the plasma, M is the mass of the particle, and m is the electron mass. For the typical values V = 100 volts, $J = 10^{-3}$ amperes per cm^2, and argon ions with $\sqrt{M/m} = 270$, the value of d is approximately 0.1 cm. On the basis of this, one might think that grid control could be attained by simply using such small grid openings (or large grid biases) that these space charge sheaths would choke off the current paths through the grid openings. This can be done in some cases[47] but there are unexpected complications that arise from interrelations between the factors in equation 7. As the potential V is increased to increase d, for example, the discharge becomes throttled and tends to operate with a higher conduction drop. This usually results in increased ion generation and an increase in the quantity J so that the expected increase in d is cancelled out. A way to avoid this difficulty is to use an auxiliary discharge[48] to generate the ionization in a hot cathode tube and restrict the main anode potentials to values below those necessary for the conduction electrons to ionize. There is a very close resemblance between this type of operation and that of a junction transistor.[49]

The gaseous plasma is a prolific source of noise.[50] In addition to the kT noise, which finds use as a standard noise source,[51] there is often a strong component associated with the erratic notion of sheaths in the current conduction path through the plasma.[47] From a practical standpoint these noises usually relegate gas discharge switching devices to high signal level applications and often necessitate careful shielding from other circuit components.

The length of time required to terminate conduction is not necessarily as long as that required for the gas to totally deionize. This is particularly true with ignitrons and thyratrons. The mercury pool discharge in the former tube can be terminated by making the anode negative for as short a time as 10^{-9} seconds.[52] Disruption of the discharge occurs because the emission mechanism has been disturbed. The residual current from the decaying plasma starts with a value approximately one hundredth of that flowing during conduction and dies away with time constant in the order of 10^{-4} seconds. The mercury pool discharge is rather unique in that it is rather difficult to start but can be easily and rapidly terminated. Thyratrons behave oppositely. To stop conduction in the thyratron the anode potential is removed so that no new ions can be generated. The residual plasma then dies away principally by ambipolar diffusion to the bounding surfaces with a time constant[53]

$$\tau = \frac{\lambda^2}{D_a},$$

where λ is the characteristic diffusion length of the interelectrode space, and D_a is the ambipolar diffusion constant. For a spherical space $\lambda = r/\pi$. The quantity D for one millimeter of gas pressure and thermal equilibrium conditions between the ions, electrons, and room temperature atoms ranges from about 20 cm^2/sec for xenon and mercury to about 500 cm^2/sec for helium. As the density of the charged particles in the plasma decreases the quantity J in equation (6) decreases until, finally, the sheath thickness becomes great enough to choke off the grid holes. From this time on it is possible to reapply the anode potential without causing breakdown. The effective dimensions of the tube are reduced by the residual plasma still present so that the tube will not regain its full insulating characteristics until the tube is completely deionized. The time after which anode potential can be reapplied without causing breakdown is known as the recovery time and commonly has a value of the order of 10^{-4} seconds for mercury and noble gas-filled thyratrons. Hydrogen-filled thyratrons have recovery times of the order of 10^{-5} seconds. In general, the recovery time is minimized by using (1) a low pressure gas of low molecular weight, (2) small tube dimensions, and (3) large grid biases.

To terminate a cold cathode discharge in the trigger tubes previously described, the anode potential has to be held below the sustaining potential until the gas is almost completely deionized. This requires hundreds or even thousands of microseconds.

In mercury and noble gas filled tubes recombination on the bounding surfaces plays the major role in deionization. Direct recombination in the volume between electrons and ions is most improbable just as is direct recombination between holes and electrons in a semiconductor. What is needed is a third body so that the momentum and energy conditions for recombination can be satisfied. In a radar TR tube this is provided by the addition of water vapor molecules to the parent noble gas. When the discharge produced by the radar transmitter pulse ceases, the plasma electrons attach to the water vapor molecules and very rapid recombination with positive ions then ensues.[54] This process provides deionization times of a few microseconds. The effect of water vapor on cathodes makes this technique unsuitable for most gas tube devices. TR

TABLE III

	Gas Discharge				
	Cold Cathode	Hot Cathode		Vacuum	Semiconductor
	trigger tube	ignition	diode or thyratron	diode or grid controlled	junction diodes and transistors
Non-Conduction					
Breakdown voltage	10^2	10^3	2 x 10^4	10^4-10^5	10^2
Breakdown fields (volts/cm)	10^2	10^3	5 x 10^4	~ 10^5	10^4 - 10^5
Residual back current (amps)	0	0	0	0	10^{-6}
Conduction					
DC impedance (ohms)	10^3	10^{-2}	1	10^3 - 10^2	1
drop (volts)	10^2	10	10	10^2	1
Average current (amps)	10^{-1}	10^3	10	10^{-1} - 10	1
Average current density (amps/cm^2)	10^{-3}	10^4	1	1	1 - 10
Required aux. power (watts/amp) current	0	0	10	15	0
Switching Properties					
On time (secs)	10^{-5}	10^{-4}	10^{-7}	10^{-9}	10^{-6}
Off time (secs)	10^{-3}	10^{-8}	10^{-5} - 10^{-4}	10^{-9}	10^{-6}
Practical Frequency Limit (cps)	10^3	10^2	10^4	10^9	10^6
Power gain close to zero freq. (db)	20	20	50 - 80	80 - 100	40
Input impedance (ohms)	10^3	1	10^5	10^6	10^2
Miscellaneous					
Nominal Life (hours)	10^4	10^4	10^3	10^3	10^3
Noise (db above thermal)	~ 40	~ 70	~ 70	5	10 or greater
Ambient temperature (o_c)	up to 10^2	~ 40	up to 10^2	up to 10^2	up to 10^2
Total device volume per unit conduction current (cm^3/amp)	10^2-10^3	10 - 10^2	10 - 10^2	10^2 -10^3n	1 - 10

tubes, in essence, are gas filled sections in the waveguide between a radar receiver and an antenna used in common with the radar transmitter. During the transmitter pulse the TR tube ionizes and prevents transmitter energy from entering the receiver. After the transmitter pulse has disappeared it is obviously desirable to have the TR tube deionize as soon as possible so that the antenna-receiver path can open.

The salient, "best performance", properties of commercially obtainable gas discharge switching devices are summarized in Table III. Vacuum tube and semiconductor devices are included for comparison. The data have been compiled from tube manuals, commercial bulletins, and the sources noted earlier. The great variation in design and mode of operation makes it impossible to give any more than a rough order of magnitude figure for the characteristic properties. Gas and vacuum devices have been under development for a much longer time than semiconductor devices. Consequently, their present day performance, as indicated in the table, might be expected to be very much closer to the theoretical maximum than that of semiconductors. Semiconductor devices are being improved very rapidly.

It is obvious that semiconductor devices potentially, if not already in practice, have many advantages over gaseous devices used as switches. How widely they will supersede the latter will depend upon the unit production cost and how well the various engineering and production problems can be ironed out.

Light Sources

The light generated from all the sources in use today derives from excited atoms or molecules in gases or in solids. In the switches and control devices just considered radiation is an undesirable by-product of the conduction process because it represents energy loss that ultimately shows up as an increase in the potential required to pass the current through the ionized gas. Thus, in making a gas discharge light source, one does the opposite of what is done in a conduction device, and channels as much energy as possible into atomic or molecular excitation processes. The great number of excited levels that exist below the ionization energy level is good insurance that most of the energy supplied to the ionized gas goes into excitation processes. The energy in the light of the desired wavelength is enhanced by proper choice of the gas filling and the operating conditions. The percentage of energy lost to electrodes in the form of heat can be minimized by making the volume of the ionized gas relatively large. This is done, for example, in fluorescent lamps.[55]

In the plasma column of a modern fluorescent lamp, approximately 85% of the input energy is delivered as light.[55] Of this, about 60 to 70% is radiation at one wavelength, the 2537-A line of the mercury vapor used as the gas. This, however, is not directly usable for illumination and must be transformed into visible light by the phosphor coating (a solid) on the bulb. This transformation is accomplished with an efficiency of about 30%, a reminder that the fluorescent lamp is really a convenient marriage between the gaseous and solid states.

As with conduction devices, the free electrons in the gas are the principal agents for excitation of the gas atoms and molecules. Then, unless an electrodeless discharge using high frequency excitation is employed, the cathode problems previously considered have to be taken into account. The electron emission in a fluorescent lamp is provided by the thermionic emission caused principally by heating of the cathode from ion bombardment. The cathodes are heated by line current during the starting period. Once the discharge starts the heating proceeds by ion bombardment and the line current is no longer required. Self heating is enhanced by the use of small diameter cathode wires which minimize heat conduction loss into the base of the lamp. These wires are coated with an oxide that provides a low work function to make available significant electron emission at relatively low temperatures.

The mercury, sodium and other gas discharge lamps used for illumination operate with thermionic emission. In fact, any gas discharge light source used for illumination calls for the high electron emission density provided by thermionic emission if the radiation density is to be high enough to be practical. This follows because the radiation density is proportional to the free electron density in the gas and this, in turn, is proportional to the electron current density, all other parameters* being held constant. The ubiquitous neon sign, which is a special effect device and not really useful for illumination, functions with the low emission density provided by pure secondary emission. The little neon bulbs used for indicator purposes fall into the same category in having a relatively low density of output radiation.

*The electron temperature, in particular.

The fluorescent lamp has been studied in great detail and provides a good example of the operation of basic physical processes in determining the energy balance in a light source. This energy balance is described by the data in Table IV.[55] The data applies to the commonly used 40 watt fluorescent lamp filled with mercury vapor plus several mm. of argon. The argon gas facilitates starting when the lamp is cold and the mercury pressure low. When the lamp warms up the mercury takes over in the discharge. The external circuitry loss takes place in the resistance and inductance of the ballast device that functions in the starting operation and also in keeping the lamp current at the proper level during operation. Energetic ions and electrons striking the anode and cathode account for the electrode power loss. At the cathode this serves the useful purpose of generating thermionic emission.

TABLE IV

	Watts	% of Total Input
Total input power	48	100
Loss in external circuitry	8	16.7
Loss in tube at electrodes	8	16.7
Total loss outside of plasma	16	33.4
Total light output from plasma	32.0	66.6
Visible light output from plasma	0.9	1.9
Light output of 2537-A wavelength	24.0	50.0
2537-A light converted to visible by phosphor	8.2	17.1
Total usable light output	9.1	19.0

Because of the large mass difference between electrons and neutral atoms, there is very little electron energy transferred to the neutral gas atoms by elastic collisions. The ions are much more capable of transferring energy to the neutral gas but can be expected to pick up appreciable energy only in the high fields of the thin sheath adjacent to the cathode and, consequently, will make very few collisions with neutrals.* It is in this same

*This consideration is in error if there are sheaths inside the plasma, as there will be if striations are present.

sheath that the cathode electrons pick up the energy necessary to ionize and excite. Due to interactions, as yet not fully understood, the monoenergetic stream of electrons leaving the cathode is scattered into a randomized energy distribution shortly after entering the plasma. The resulting electron temperature depends upon the type of gas, the gas pressure, and the tube dimensions. It commonly is of the order of 10^4 °K in fluorescent lamps, glow discharges and thyratrons.

Compared with the incandescent lamp, which only converts about 4% of the electrical input power to usable light, the fluorescent lamp is a very efficient device and is widely used. However, it is interesting to note that it has not completely supplanted the incandescent lamp. The ratio of incandescent to fluorescent lamps in use in this country is approximately 4:1.[56] The ratio of sales last year was 10:1.[56] The main reason in the lack of complete supremacy is largely the greater complexity and total cost of the fluorescent lamp, plus its fixture with the starting and ballasting mechanism.

The fluorescent lamp is extremely efficient because it is a very selective transformer of electric into light energy. Other forms of gas discharge light sources are not so effective in this respect but have other highly desirable features unobtainable by any other presently known type of source. One of the most important of these features is light intensity. The arc discharge is a champion in this respect, being capable of delivering in continuous operation up to 1200 candles per square mm. of radiating surface.[55] This compares with a candle density of approximately 1 candle per square mm. for the incandescent lamp. The high temperature and light output from the arc is a consequence of its extremely high power density. This can be as high as 10^4 watts per cm^3. It seems quite impossible that any light source delivering the light intensity of the arc could exist in anything but the gaseous state. Therefore, it is probable that the arc will enjoy a monopoly in this field regardless of the great improvements that will probably be made in solid state light sources.

There is a great variety of arc light sources designed for specific purposes. The carbon arc is widely used for projection, but mercury arc for the production of ultraviolet radiation and certain lighting applications, the zirconium arc for a point light source, and the sodium arc for road illumination. Other types of arcs, cadmium, zinc, and tellurium, are employed in the production of certain wavelengths. Because of their greater electrode losses and loss of energy at unusable wavelengths, the arcs have an efficiency that is about half that of the fluorescent lamp.

The relatively short time constant of the physical processes in a gaseous discharge makes them useful in providing light outputs of short duration. The thermal time constant of the incandescent lamp rules it out if light durations shorter than a tenth of a second are desired. The light producing excitation processes in a gas discharge can be initiated as rapidly as a high density of energetic electrons can be produced. This, as pointed out in a preceding section, can be accomplished in times of the order of a microsecond. When the input electrical energy is removed most of the light will die away with the decline in electron density and energy. Depending upon the gas parameters, type and pressure, this might be expected to occur with a time constant of the order of ten to hundreds of microseconds.

In a practical application, a large condenser is charged to a high voltage and then suddenly switched across the discharge tube. This is done, for example, with the flash tubes used for high speed photograph.[56,57] A typical helium-filled tube of this sort has a momentary input power of several hundred thousand watts and the light flash duration is of the order of 10^{-4} seconds. The light flash is of the order of a million lumens at a color temperature of about 4000° K. One limitation on the allowable peak power input is the mechanical damage incurred by the glass envelope from the pressure shock wave set up within the tube. The life of the device is a function of the number of flashes delivered and the physical deterioration that occurs during each flash. The same limiting factors described for the gas tube switches might be expected to be operative here also.

As time passes, it is inevitable that gas discharge light sources will find more competition from solid state devices. Within a few years, for example, the light output efficiency of luminescent panels has risen from 0.1 percent to 2 percent with no immediate theoretical limit in sight.[56] It should be remembered that the first practical electrical light source, the incandescent lamp, is a solid state device. The light arises from the thermal excitation of the atoms in the crystal lattice of the filament. It is relatively inefficient because so many of the excited levels are at very long wavelengths, providing heat instead of visible light. The new solid state devices promise to be very much more efficient because of the possibility of exciting only a few discrete wavelengths that fall in the visible. The basic principles closely parallel those of gas discharge light sources. Highly mobile charge carriers are required as the excitation agents. There must be some means of delivering energy to these agents, and once atoms have been excited to produce radiation this must be somehow delivered to the outside. The factors that make the solid state devices promising are: (1) Due to thermal generation there is normally a high density of mobile charge carriers already present in the solid, obviating the need for cathodes and special starting mechanisms; (2) The energy can be delivered to these carriers with electrical fields much in the same way as with a gas discharge; (3) There seems to be no good reason why a high fraction of the energy delivered to carriers cannot be useful in the excitation process, and (4) It seems to be

TABLE V

Property	Incandescent	Glow Tube	Fluorescent	Arc Carbon	Arc Mercury	Xenon Flash Tube	Experimental Luminescent Panel
Efficiency							
Lumens* output per watt input	17	24	70	5	65	30	10
% efficiency	4	6	20	1	15	8	2.4
Intensity							
Candles per sq. mm	~ 1	10^{-2}	2 x 10^{-1}	1200	~ 500	~ 10^4	10^{-1}
Foot lamberts**	~ 10^6	100	1900	10^7	~ 10^7	~ 10^8	1000
Brightness temperature (^oK)	2800	-	~ 4000	~ 5000	-	4000	?
Input energy per unit of radiating volume (watts/cm³)	~ 1	~ 10^{-2}	10^{-1}	~ 10^4	~ 10^3	> 10^4	perhaps 10^{-1}
Miscellaneous							
Life (hours)	~ 1000	> 10,000	1000-10,000	?	?	> 10^4 flashes	?
Flash duration (sec)	~ 10^{-1}	~ 10^{-3}	-	-	-	10^{-4}	?
Spectral distribution	towards red	depends on gas	fairly flat over visible	(peaked near 4000-A)	strong in U.V.	daylight	?
Geometry of active volume	somewhat flexible	flexible	flexible	point source	point source	flexible	very flexible

*A lumen is a unit of rate of emission of light energy and equals {0.00161 watts for 0.556 micron light; 12.6 candles}

**A lambert is a unit of rate of emission of light energy per unit area of source. One square foot emitting one lumen is a foot lambert.

possible to deliver this radiant energy to the outside with about the same efficiency as the gas discharge. These and other possible advantages make the solid state device look like a formidable competitor, indeed.*

The salient properties of various light sources are summarized in Table V. A photograph of several types of light sources is shown in Fig. 9. Reading from left to right are: a 15 watt incandescent bulb, a 15 watt fluorescent lamp, a flow lamp, a 150 watt Hanovia high pressure xenon arc lamp, and a flash tube which is built into a reflector assembly.

Special Uses

Gas discharges are very useful as particle counters. This application involves the use of prebreakdown phenomena. In using a cold cathode diode as a proportional counter,[58] operation is carried out along region bc of the curve shown in Fig. 1.* The term "proportional" is used because the current which flows through the electrodes and the current indicating device in the external circuit is linearly proportional to the number of ion-electron pairs created by ionizing particles or radiation in the interelectrode volume per second. The applied electrode potential is not high enough to cause avalanche multiplication so that the device is restricted to cases where the flux of ionizing particles or radiation is intense enough to give an easily measurable current. When the flux is very low, as it is with cosmic rays, for example, then easily detectable currents can be obtained only if the device is operated further up on the cde portion of the curve where a very large multiplication of the primary ion-pairs can occur. This is the principle of the famous Geiger-Mueller counter. In this device one ion-electron pair can be amplified by a factor of 10^8 so that earphones or micro-ammeters can be used as indicators. After a "count" the terminal charge must be removed from the tube to prevent

*Another possible type of solid state light source (pointed out to the author by R. Braunstein) would be one wherein carriers are injected across a junction and allowed to recombine to yield recombination radiation.

*Ionization chambers operate in the region bc where there is no carrier avalanche multiplication.

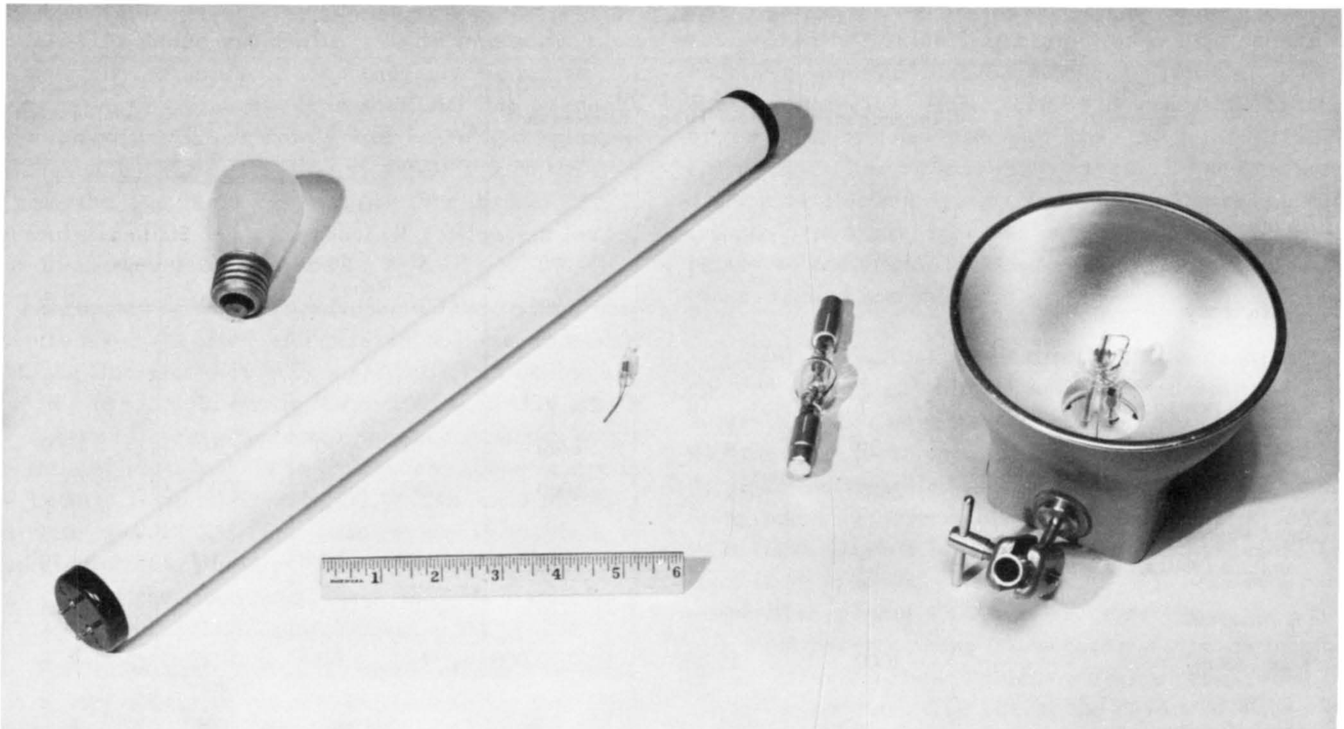

Fig. 9 – Incandescent bulb and various gas discharge light sources.

complete breakdown or at least to restore the original sensitivity. This can be done by (1) using external electronic circuitry to remove electrode potentials until the generated carriers have had time to recombine, or by (2) using an electrode configuration combined with a special gas filling that automatically returns the tube to its initial state. The latter alternative is employed in the Geiger-Mueller tube. The tube is normally filled with a mixture of argon and alcohol. Its geometry is that of a fine wire passing down the axis of a cylinder. The wire is used as the anode and the cylinder as the cathode. In brief, the avalanche process is self quenching because[59] the electron avalanches build up positive ion space charges that alter the electric fields near the anode. Alcohol and other organic vapors enhance this effect by lowering the ion mobility. The quenching process requires at least about 10^{-4} seconds so that the device cannot resolve greater than about 10^4 counts per second. Largely for this reason the G-M counter has been replaced in the laboratory by the scintillation counter.[60] This is a combination solid state-vacuum tube device wherein the brief burst of light, or scintillation, generated in a crystal by incident particles or radiation releases photo electrons from the cathode of a photomultiplier tube. These electrons are multiplied a million-fold by secondary electron emission. The device has a resolution time of the order of 10^{-8} seconds.

Other gas discharge devices using avalanche principles have been proposed as particle counters.[61] Gas-filled phototubes, such as the type 921, also use the avalanche principle. Because continuous operation is generally desired, avalanche multiplications are limited to about 10 by stability considerations. Special means have to be used to get greater amplifications.[41]

Gas discharges find very widespread employment as voltage controlling elements in electronic equipment.[62] These are called voltage regulator (VR) tubes and make use of the fact that the voltage drop of a glow discharge remains constant as long as the cathode area is incompletely covered with glow. As with the cold cathode trigger tubes discussed earlier, this type of behavior is characteristic of the normal glow discharge. Consequently, the same overall considerations with respect to life, cathode current density, and operating voltage apply to VR tubes as well as to the trigger tubes. The main emphasis is, however, on the maintenance of a constant voltage drop across the tube. For this reason, particular care must be taken with the uniformity of the cathode surface to insure that the glow can expand in area smoothly, without erratic jumps, as the current demand changes during operation. The type of the gas filling, its pressure, and the nature of the cathode surface have been determined mostly by empirical means. The desirable characteristics are: short and long stability, long life, and minimization of the breakdown or starting potential. Miniaturized VR tubes with a small current handling capacity, but having a particularly constant voltage drop over a small range of current, are called voltage reference tubes. They do not handle load current like VR tubes but, instead, provide a constant reference voltage that controls the operation of the electron tubes that handle load current.

TABLE VI

Tube Type	Operation	Operating Voltage	Current Range (ma)	Voltage Variation Over Current Range	Starting Voltage
OA2	regulator	150	5-30	2	155
OA3	"	75	5-40	5	100
OB2	"	108	5-30	2	115
OC3	"	105	5-40	2	115
OD3	"	150	5-40	4	160
5651	reference	87	1.5 - 3.5	0.1	115
5841	Corona regulator	900±15	0.002 - 0.005	15	930
5950	"	700±15	" "	"	730
Subminiature[62]	"	1800	0.05 - 0.20	10	?

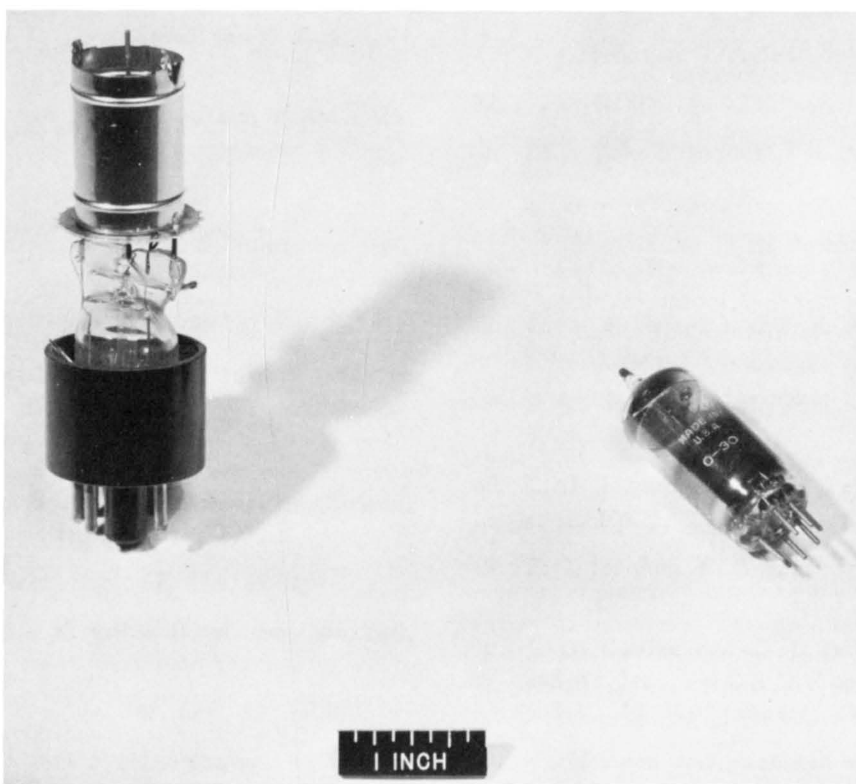

Fig. 10 — Cold cathode regulator tubes. Structure of large size tube and tube used to provide a reference voltage.

Stabilization of potentials in the kilovolt range can be accomplished with corona tubes.[62] These make use of certain properties of the corona discharge. These tubes maintain good regulation over a current range of tens of microamperes and are often used in stabilizing Geiger-Mueller counter voltage supplies.

Early promise of semiconductor diodes for use as voltage regulators has so far failed to materialize because of severe technological problems. If these problems can be solved the "Zener diode"[3] will be a potent competitor to the gas tube regulators because it is potentially capable of regulating a far larger range of voltages. This range might extend from several volts up to several hundred. Essentially this device is a p-n junction operating in the internal breakdown region of its characteristic. The very rapid rise in current with a small change in voltage supplies the voltage-regulating effect. Operation in the breakdown region does not necessarily lead to instability because, unlike the gas discharge, there is no runaway feedback effect caused by charge carriers of the opposite sign.

The operating characteristics of various voltage regulating devices are listed in Table VI. A type OD3 VR tube is shown at the top of Fig. 7. In Fig. 10 on the right of the photograph is a type 5651 voltage reference tube. At the left of the photograph a partially disassembled type OD3 VR tube is displayed to show its internal structure. The outside cylinder, comparatively large in area, is the cathode. The axial wire is the anode. Not shown in the photograph is a small wire attached to the cathode and extending almost to the anode surface. The small pressure-distance product formed by the end of this wire and the anode surface facilitates starting of the tube.

The VR tubes are usually rated to operate over a range of ambient temperatures of -55 to 90°C. Their power dissipation of about five watts is concentrated in a volume of ten to forty cubic centimeters. VR tubes might be expected to have a life of at least several thousand hours without appreciable change in operating characteristics.

E. O. Johnson

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