Title

ELECTRICAL ENGINEERING REVIEW COURSE - LECTURE XIX

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LECTURE XIX
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VACUUM TUBES

(1) DIODES

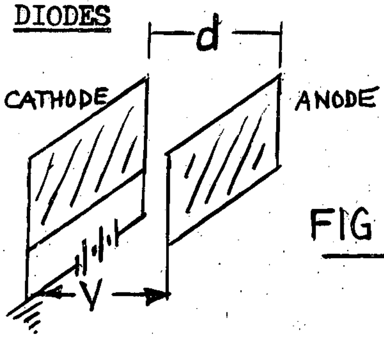

FIG 1

A diode vacuum tube consists of a filament (or cathode), with means of heating it to obtain electric emission, and a plate, or anode, which can be maintained at a voltage different from the cathode. The fundamental concepts of space charge limited currents and thermionic emission define the operation of diodes as well as all other vacuum tubes.

(A) Space Charge Limited Current

Experimental evidence shows that, for given values of cathode plate spacing d, a saturation current is reached such that further increases in plate voltage V will not increase the current flow. Below the saturation value, the current flow across the tube may be derived as follows:

(a) The electric field between the electrodes satisfies Poisson's Equation:

$$\nabla^2 V = 4\pi\rho \qquad \text{where } \rho = \text{charge/cm}^2 = f(v) \qquad (1)$$

(b) From continuity

$$I = \dot{x}\rho \qquad \begin{array}{l} \dot{x} = \text{Particle velocity} \\ I = \text{Current/cm}^2 \end{array} \qquad (2)$$

(c) From consideration of forces:

$$\text{Force} = m\ddot{x} = e\frac{dv}{dx} \qquad (3)$$

Solving Equations 1, 2 and 3 simultaneously, multiply equation 3 by $\dot{x}$:

$$e\frac{dv}{dx}\,\frac{dx}{dt} = m\,\frac{d\,^{1/2}(\dot{x}^2)}{dI} \qquad (4)$$

DISCLAIMER

From Conservation of Energy:

$$1/2\ m\mathring{x}^2 = eV(x) \tag{5}$$

(Kinetic energy = Potential drop)

Therefore:

$$\mathring{x} = \left(\frac{2e}{m}\right)^{1/2}(V)^{1/2} \tag{6}$$

Substituting equation 2 into equation 1:

$$\mathring{x}\,\frac{d^2V}{dx} = 4\pi I \tag{7}$$

Combining equations 6 and 7:

$$I = \frac{1}{4\pi}\left(\frac{2e}{m}\right)^{1/2} V^{1/2}\,\frac{d^2V}{dx^2} \tag{8}$$

let

$$V = V_o\left(\frac{x}{d}\right)^n \tag{9}$$

Then

$$I = \frac{1}{4}\left(\frac{2e}{m}\right)^{1/2}\frac{V_o^{1/2}}{d^{n/2}}\,X^{n/2}\ \frac{V_o}{d^n}\,n^{(n-1)}X^{n-2} \tag{10}$$

But I is not a function of x. Choose n to eliminate X:

$$\frac{n}{2} + n - 2 = 0 \tag{11}$$

$$n = \frac{4}{3}$$

Therefore:

$$V = V_o\ \left(\frac{x}{d}\right)^{4/3} \tag{12}$$

Interpreting Equations 12, one sees that the plate voltage, as seen by the filament, is shielded out by some phenomena. The current becomes (from equations 10 and 12):

$$I = \frac{1}{9\pi}\left(\frac{2e}{m}\right)^{1/2}\frac{V_o^{3/2}}{d^2} - \frac{4}{9} \tag{13}$$

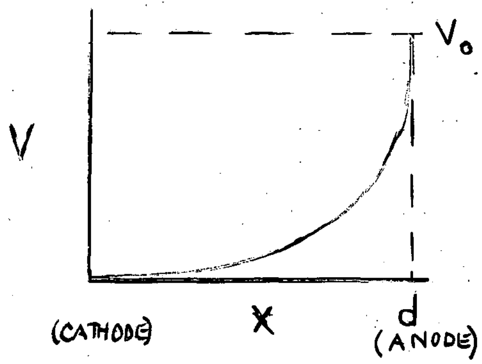

FIG 2

(This expression is called Child's Equation)

Above the saturation current, neither increases in the rate of emitting particle from the filament, nor increases in the filament-plate potential, will increase the current flow. This is due to the phenomena of "space charge". As more and more particles accumulate in the space between the filament and the plate, they form a cloud of the same charge as the emitted particles, and hence, drive the emitted particles back to the filament.

For electrons, space charge limits occurs at rather high values of current:

Let

$$\left.\begin{array}{l} V_o = 300 \text{ Volts} \\ d^o = 1 \text{ millimeter} \end{array}\right\} \quad \text{Then } I = 3 \text{ amps/cm}^2$$

For heavier particles, the limitation occurs at much smaller values.

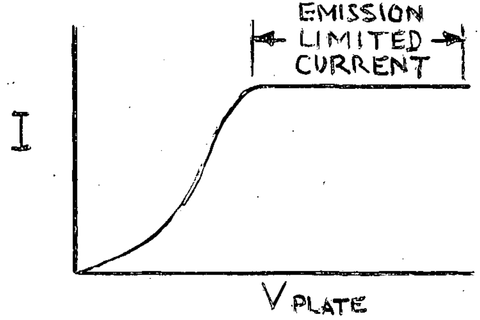

FIGURE 3

Vacuum tubes are often run in the space charge limited range to obtain stable constant currents. This is called running "Emission Limited".

(B) Thermionic Emission

At a certain temperature, different for each material, metals will emit electrons in a fashion anologous to vapor produced by a boiling liquid. The particles gain an energy sufficient to escape from the holding potential of the surface. Two classes of electrons exist in a metal, (1) The bound electrons which are part of the atoms and (2) The free electrons which circulate between the atoms of the material. These free electrons, held by a potential of the order of 4 volts, are the ones which are emitted when the metal is heated.

Consider a Maxwellian energy distribution of the electrons in a metal:

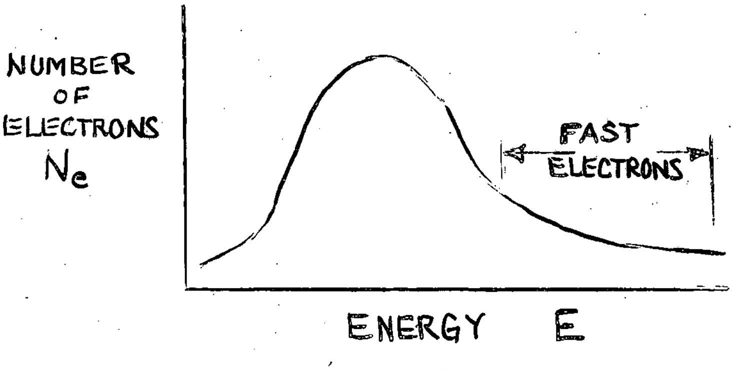

FIGURE 4

$$N_e(E)dE = CE^{1/2}e^{-E/kT} \qquad (14)$$

k = Boltzman Constant

Then the number of fast electrons, which have a energy greater than the "work function", φ, of the metal ($E > \varphi$) and can thus escape:

$$N_{(E>\varphi)} = C'e^{-\varphi/kT} \tag{15}$$

In terms of current this is:

$$I = KTe^{-\varphi/kT} \qquad T = \text{Temp.—°Kelvin} \tag{16}$$

Put in the observed value of φ(5 volts). Then KT must be the order of 2 volts or 24,000° K, to agree with observed evidence. Thus, if electrons had a Maxwellian Disbribution of energy, the metal would not begin to emit until the temperature was the order of 24,000° K. But experiemtnal evidence indicates metals emit at 2,000° C. Thus, the electrons do not have Maxwellian energy distribution in the metal.

A theoretical explanation which more accurately fits experimental observations was developed by Richardson and Pauli USING Quantum Mechanics and the statistics of Fermi and Dirac.

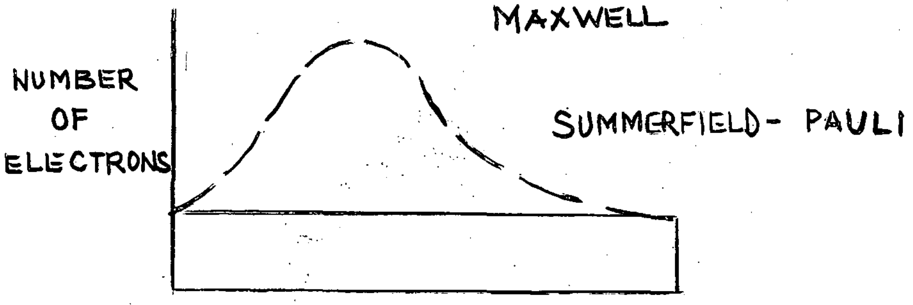

FIGURE 5

At very low temperatures surplus electrons exist in a free state which gives them far more energy, than the temperature of the metal permits, because they cannot occupy lower energy states from the arguments of Quantum Mechanics. Once emission has started, the Maxwellian distribution is more and more closed approached until, for high temperatures, it holds. (At very high temperatures, the Summerfield-Pauli equations yield the Maxwellian form). The same phenomena is noted for gases. At room temperatures, the molecules of a gas have a Maxwellian energy distribution. At temperatures near absolute zero, the gas behaves as do electrons when emission is just starting.

In a Diode electron tube, current can pass from filament to plate when no potential exists between them because of the thermal energy of the "Boiled off" electrons.

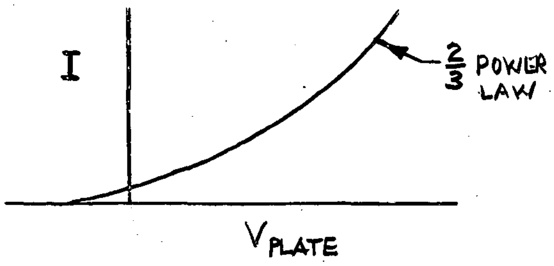

FIGURE 6

Diode tubes are used principally as detectors, and as rectifiers for either control or power purposes.

(2) TRIODES

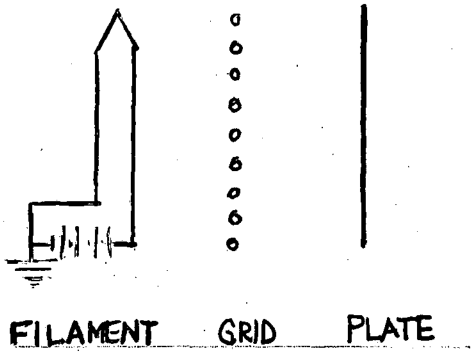

FIGURE 7

In a triode tube an open wire electrode, called a grid, is inserted between filament and plate. A small change in grid voltage can now make a large change in the filament-plate current. Thus, a small quantity of energy can be used to regulate a large quantity. At cut-off, the grid, by being made negative with respect to the filament, stops all emitted electrons.

If the grid is close to the cathode, only a small grid voltage is required to swing large plate voltages. If the grid is close to the plate, grid voltages becomes the same order as cathode voltages. If grid wires are far apart, it is hard to "cut off" the tube. Where one is using a triode as a switch, one wants close grid wire spacing. For use as a Modulator, coarse wire spacing is used.

(3) TETRODE (Screen Grid Tube)

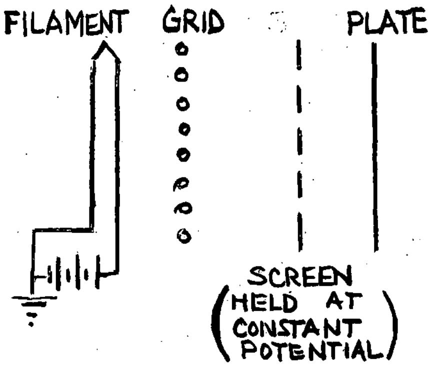

FIGURE 8

If a screen is inserted between grid and plate and held at constant potential, then when the plate voltage gets above the screen voltage, the plate voltage remains constant. This gives a constant current region. This arrangement also insulates the grid from the plate, so that a jumpy plate signal will not disrupt the control exerted by the grid.

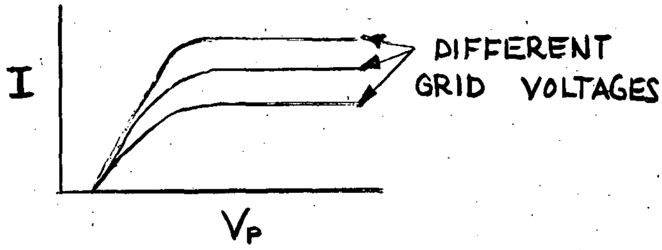

FIGURE 9

(4) PENTODE TUBE

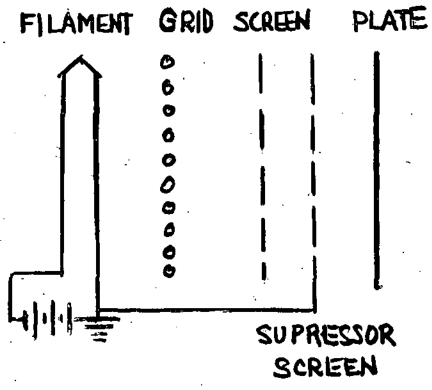

FIGURE 10

If another surpressor screen is inserted between the screen and plate, and tied to cathode potential, it will drive secondary electrons emitted by the plate back to the plate and make for more stable operation.

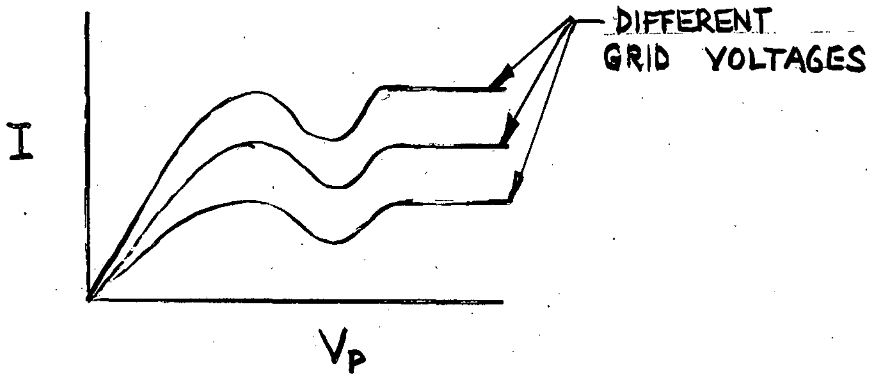

FIGURE 11