United States Patent [19]

Breaux

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[54] **STABILIZED, OPTIMIZABLE, GASEOUS ELECTRICAL DISCHARGE**

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[52] **U.S. Cl.** **331/94.5,** 356/85, 313/179

[51] **Int. Cl.**.....**H01s 3/00**

[58] **Field of Search** 331/94.5; 313/179; 330/4.3

[56] **References Cited**

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[57] **ABSTRACT**

A direct current (DC), transverse discharge, gaseous, slotted hollow cathode laser having an electrically indirectly heated oxidized tungsten, or molybdenum cathode, heated to thermionic emission in the presence of cesium vapor adsorbes cesium atoms and over a defined temperature range thermionic emission occurs in inverse proportion to the temperature of the cathode stabilizing the emission, precluding the formation of "hot spots," and the relative low cathode fall voltage is varied providing an optimized amount of energy to the electrons as they are accelerated through the cathode fall voltage.

6 Claims, 10 Drawing Figures

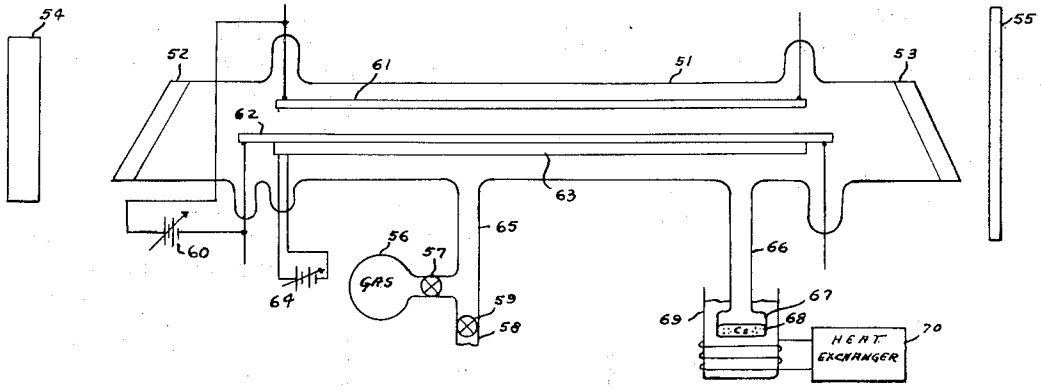


Fig-1

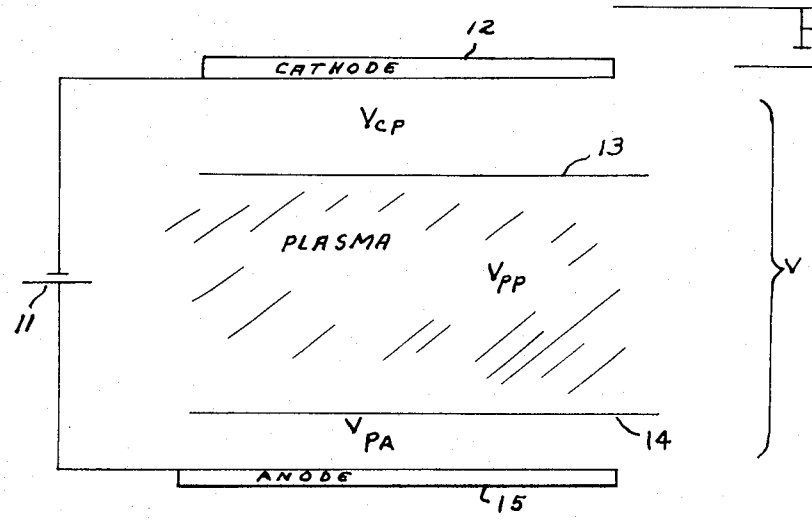


Fig-2

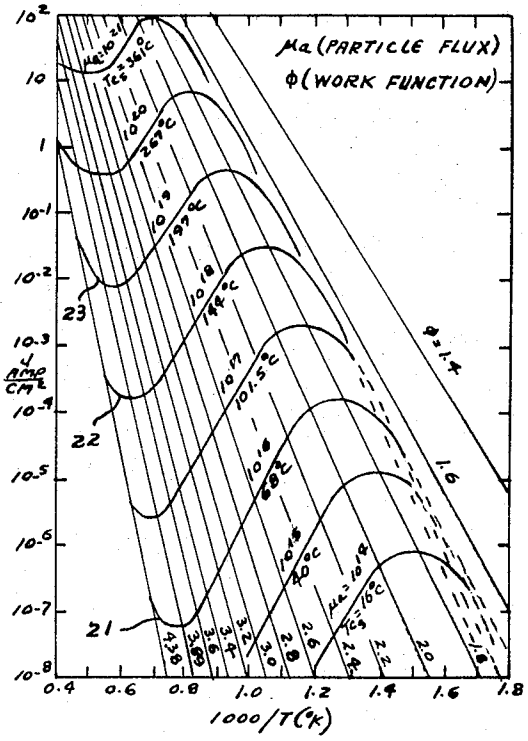
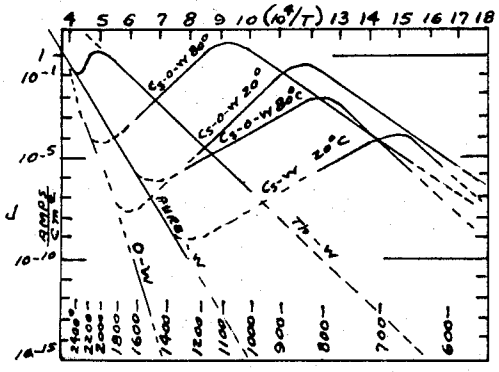


Fig-3



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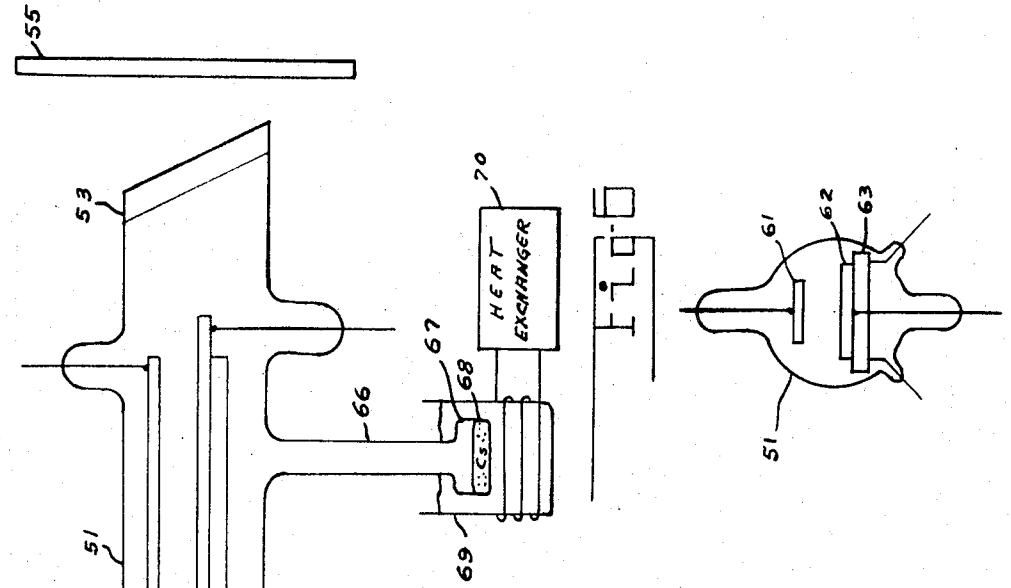


FIG-5

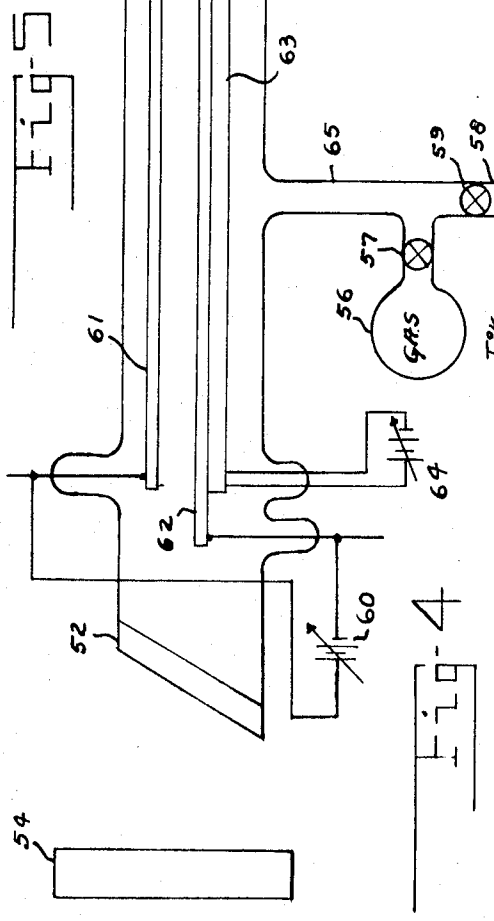


FIG-4

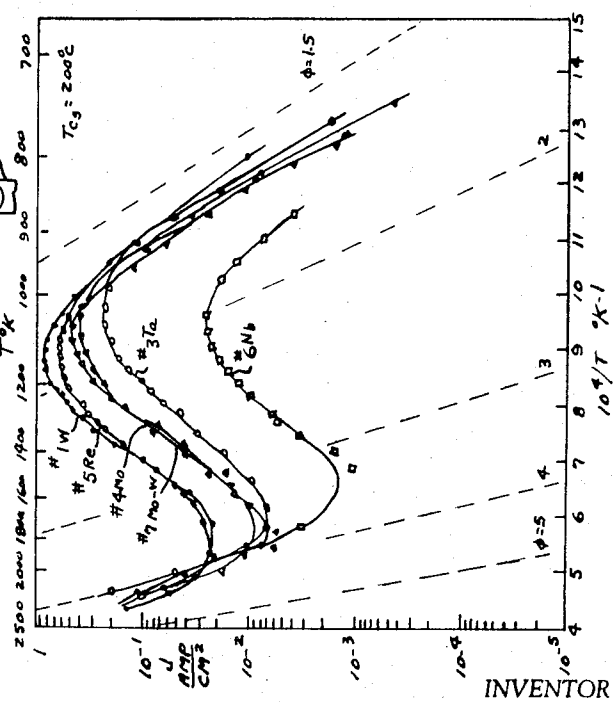


FIG-6

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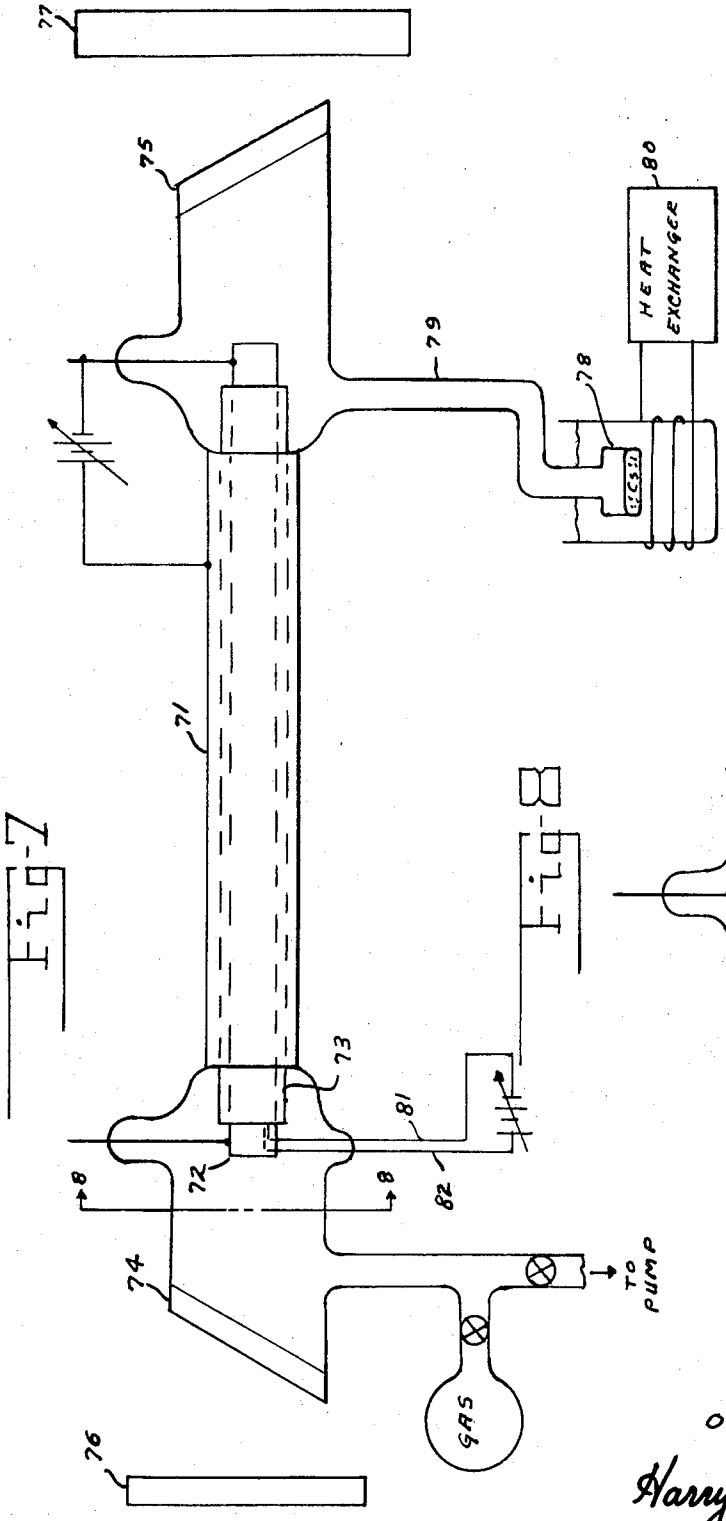
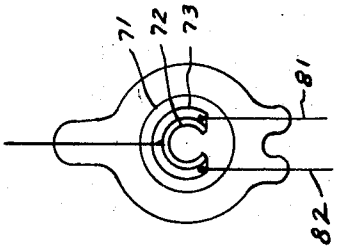


Fig-7

Fig-8



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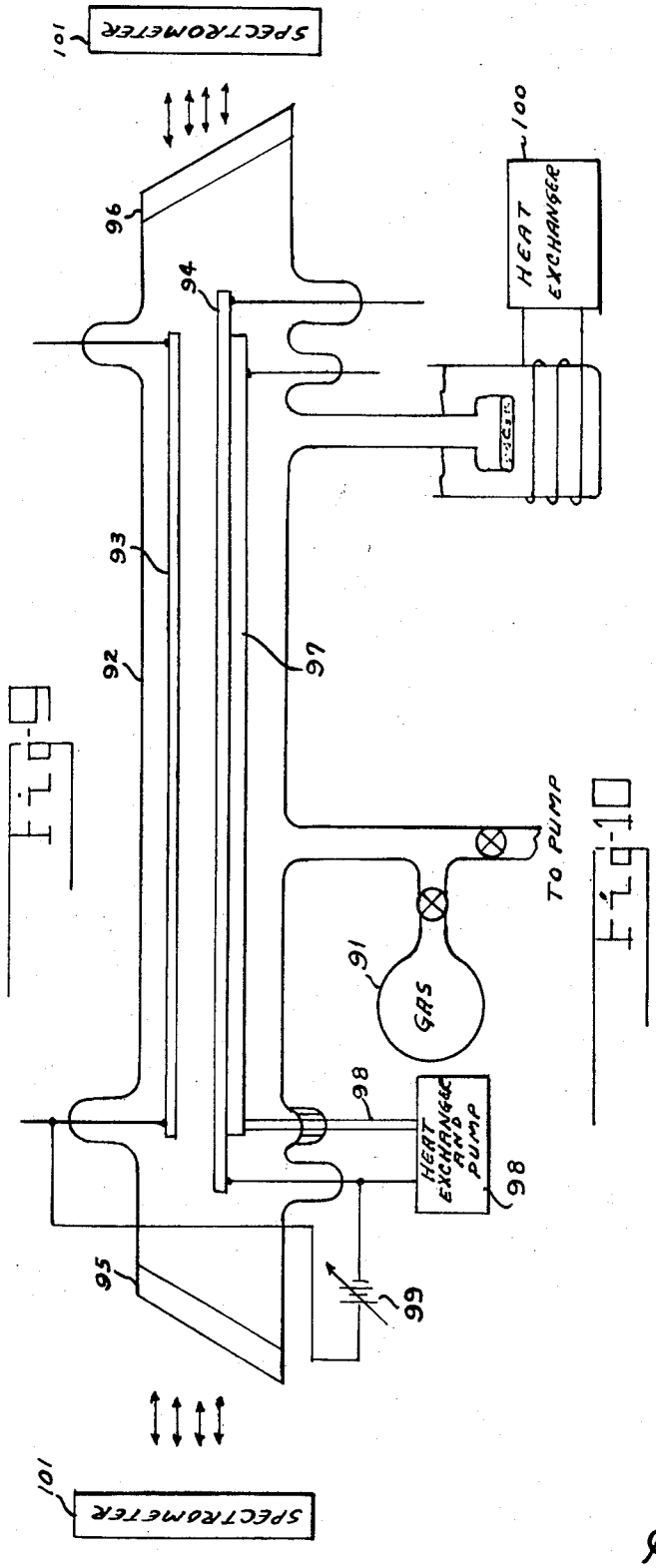
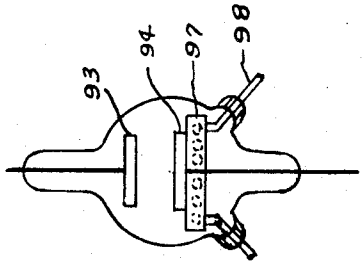


Fig-9

Fig-10



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STABILIZED, OPTIMIZABLE, GASEOUS ELECTRICAL DISCHARGE

BACKGROUND OF THE INVENTION

The field of this invention is in the art of thermionic cathodes and more particularly that of thermionic cathodes for gaseous lasers and electric discharge gas analyzers.

Thermionic emitters are well known as are the effects of adsorbed films on the emitters. Reference is made to Vol. 3 of "The Collected Works of Irving Langmuir" edited by C. Guy Suits, Pergamon Press Inc., (1961) particularly at pages 284 to 289 and pages 311 to 313; Vol. 17 of "Advances in Electronic and Electron Physics" by L. Marton, Editor, Academic Press (1962), pages 148 and 149; Physical Review Vol. 23, pages 112 and 113 (1924); "Materials and Techniques for Electron Tubes" by W. H. Kohl, Reinhold Publishing Co., pages 299 to 302 (1960); and "-Direct Energy Conversion" edited by W. Sutton, McGraw-Hill (1966), section "Thermionics" page 243. For the structure of cathodes and heaters reference is made to "Radiotron Designer's Handbook," by F. Langford-Smith, Amalgamated Wireless Valve Co., pages 4 and 5 (1953).

Gaseous, DC, transverse discharge including slotted, hollow, cold cathode (non-thermionically emitting) are well known, an example being the paper "Transverse-Discharge Slotted Hollow-Cathode Laser" by W. K. Schuebel in IEEE Journal of Quantum Electronics, Vol. QE–6, No. 9, Sept. 1970. Gas lasers using either elemental gas or molecular gas are well known. An example of excitation using monoenergetic electrons from a heated cathode is given in the text "Gas Lasers," by C. K. N. Patel commencing at page 99. The structure disclosed on page 100 attempts to stabilize cathode operation by the use of a grid. In addition to the problems of grid emission, destruction of the delicate cathode rapidly takes place from ion bombardment penetrating the grid. The grid also greatly complicates the structure and prohibits uniform emission from the cathode into the plasma. Thus this structure has proved to have only very limited success.

SUMMARY OF THE INVENTION

A gaseous electrical discharge system having a stabilized, controllable thermionic cathode for feeding electrons of optimizable energy content into a gas plasma.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a schematic representation of the electrical potentials supporting a plasma;

FIG. 2 is a plot of a family of characteristic curves of electron emission density from a thermionic molybdenum cathode in cesium vapor;

FIG. 3 is a plot of the thermionic electron emission characteristics of pure tungsten, thorium-tungsten, and oxidized tungsten cathodes, with and without the presence of cesium;

FIG. 4 is a plot of the electron emission characteristics from cathodes fabricated from the five elements, Niobium (Nb), Tantalum (Ta), Molybdenum (Mo), Rhenium (Re), and Tungsten (W), and a 50—50 by weight Mo-W cathode in cesium vapor;

FIG. 5 is a schematic-pictorial representation of an embodiment of a laser having a flat thermionic cathode;

FIG. 6 is a pictorial representation of an end view of the gas enclosing structure of FIG. 5;

FIG. 7 is a schematic-pictorial representation of an embodiment of a laser having a slotted hollow thermionic cathode;

FIG. 8 is a pictorial representation of an end section view of the structure of FIG. 7;

FIG. 9 is a schematic-pictorial representation of an embodiment of a system for analyzing the characteristics of gaseous plasmas; and

FIG. 10 is a pictorial representation of an end view of the gas enclosing structure of FIG. 9.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Consider the gaseous electrical discharge as presented schematically in FIG. 1. The gaseous substance may be either a true gas, or vapor or a combination of gas and vapor. The discharge voltage V (volts) from the voltage source 11 subdivides into essentially three voltages. The voltage drop from the cathode 12 to the upper edge of the plasma 13, which is conventionally called the "cathode fall" voltage and designated V_{CP} is one portion of the total voltage. Another portion is the voltage drop from the lower edge of the plasma 14 to the anode 15, termed the "anode fall," V_{PA}; and the remaining voltage drop across the plasma from the cathode fall edge 13 to the anode fall edge 14, termed the "plasma fall," V_{PP}. Expressed mathematically by $V = V_{CP} + V_{PP} + V_{PA}$. With a particular gas, and under the same conditions, as the voltage V is varied essentially only the cathode fall voltage will change; the voltage across the plasma and that of the anode fall voltage both remain substantially constant.

In certain applications of gaseous electrical discharges, it is desirable to have a particular value of cathode fall V_{CP} in order that the electrons being accelerated through it attain a certain energy. A particular example is the gas laser discharge which requires particular values of electron energy for efficient population inversion to occur in the gaseous substances involved in the electrical discharge.

"Cold cathode" (non-thermionically emitting cathode) gaseous discharge lasers are well known, an example is described by W. K. Schuebel in the paper "-Transverse-Discharge Slotted Hollow-Cathode Laser" appearing in the IEEE Journal of Quantum Electronic, Vol. QE–6 No. 9, September 1970 at pages 574 and 575. A cold cathode discharge, as opposed to a thermionically emitting cathode discharge requires a certain value of V_{CP} in order to sustain a usable discharge with the value of V_{CP}, in many applications, much higher than the value required for efficient electron energy. The argon-ion laser is a typical example in which that is the situation. In an argon-ion laser the optimum electron energy requirements are met with a voltage of approximately 28 volts, corresponding to the ionization potential of the singly-ionized argon ion; however, cold cathode discharges for the argon-ion laser require a discharge voltage of approximately 300 volts.

A "hot cahtode" (thermionically emitting cathode) discharge can be used to eliminate the large, inefficient discharge voltages since a hot cathode does not require a large value of V_{CP} to sustain the discharge and V_{CP} can be adjusted to the electron energy required for a particular application; however, a conventional hot cathode employed in place of a cold cathode results in an inherently unstable, unsatisfactory system, as large area hot cathodes operated at saturation develop "hot spots" with current tending to accumulate at these spots. This not only results in unbalanced operation of the discharge, but the hot spots become hotter due to increased emission and by a regenerative effect the emission "runs away" at the hot spots to the destruction of the cathode.

Consider the basic thermionic emission equation of Richard-Dushman:

$J = AT^2\exp(-q_eV_{Me}/kT)$ where,

T = cathode temperature (°K)

q_e = electron charge = 1.6×10^{-19} coulombs

k = Boltzmann's constant = 1.38×10^{-23} Joules/°K

A = "Universal constant" = 1.2×10^2 amperes/cm^2°K^2

V_{Me} = work function of cathode (volts)

J = current density (amperes/cm^2)

Loosely summarized, this states that increases in the temperature of the cathode (emitter) result in increased thermionic emission. In the conventional application of thermionic emitters in vacuum tubes cathode emission is limited by the space charge effect and hot spots with thermal run-away has not been a serious problem.

It has been known for many years (see, previous "-Background of the Invention") that over a defined range of temperature that the work function V_{Me} of the cathode can be changed significantly by adsorbed gases (or vapors), and thus also the current density J can be changed significantly. Prior to this time, this fact has been little used as generally the operating temperatures of the emitters has been outside this range and the unique characteristics evolving from gas absorption found in this range of temperatures has not previously been needed. It has been found that cesium is the preferred vapor to be absorbed by the cathode for this invention, other vapors of the alkali class such as gaseous rubidium are generally not as suitable or as easily utilized as cesium. Also, cesium, having the lowest ionization potential, and hence ease of ionization, allows its use as ions for neutralization of electron space charge in plasma formation. The curves of FIGS. 2, 3, and 4 show the current density J as a function of the temperature T of the cathode, for given values of density of the gas, cesium vapor, capable of being adsorbed on the cathode surface and changing its value of work function. Different values of t (the cathode temperature) correspond to different values of cathode coverage by the adsorbable gas (cesium vapor) with corresponding different values of current density J. The family of curves of FIG. 2 are for molybdenum cathodes in the presence of cesium vapor at vapor pressures corresponding to stated vapor temperatures on the curve. It is to be noted that on each curve a defined range of T exists in which J decreases with increases in T. For example, the operation of a molybdenum cathode in the presence of cesium vapor at a vapor temperature of 68°C is represented by curve 21. In this particular curve a maximum J of approximately 10^{-4} amp/cm^2 occurs at a temperature of approximately 1.3 of 1000/T, i.e., a temperature of approximately 770°K. As the temperature increases to approximately 0.8 of 1000/T, or a temperature of approximately 1,250°K, the emission has decreased to approximately 10^{-7} amp/cm^2. To shift the range of the negative temperature characteristics to provide higher or lower values of controlled J it is merely required to change the temperature of the cesium vapor to reach another curve of the figure, or any position in between. In this manner by controlling the temperature of the cesium vapor, and the temperature of the cathode, a value of cathode fall voltage may be set to optimize the value of electron energy possessed by the electrons entering the plasma, and by the operation of the cathode over the range of negative temperature to emission characteristics a uniform, stabilized, cathode devoid of hot spots is obtained. Physically stated, any areas on the hot cathode tending to form hot spots, with increasing J, will be counter-balanced by the loss of cathode coverage with the resulting tendency to reduce J; any areas tending to cool, with decreasing J, will be counter-balanced by an increase of cathode coverage (by cesium atoms) and the resulting tendency to increase J.

As an example of a simplified embodiment utilizing the foregoing characteristic to obtain a stabilized, optimizable discharge for argon plasma, a molybdenum cathode with cesium vapor is used. The cesium vapor is from a cesium reservoir at a temperature T_{CS} of 450°K (177°C); this is equivalent to a cesium vapor pressure P_{CS} of approximately 2×10^{-2} Torr, with a cesium density n_{CS} of approximately 6×10^{14}/cm^3. At an operating point T of approximately 1,000°K the current suffers a 1.24 percent decrease per 1°K rise in temperature of the cathode. With a nominal argon pressure of 2 Torr, for an Argon number density n_A equal to approximately 4×10^{16}cm^3, then most of the cathode emitted electrons are in interaction with the argon. The ratio of the electron collision cross section of the argon s_A(cm^2) to the collision cross section of the cesium s_{CS} is given as follows, for a desired V_{CP} of approximately 28 volts; $s_A/s_{CS} = 1/10$ and $n_As_A/n_{CS}s_{CS} = 10$. As shown by the curves, the essentially linear portion of a curve for cesium vapor at 177°C (which would be a curve between curves 22 and 23 of FIG. 2) occurs from a J of approximately 0.1 ampere/cm^2 to a J of approximately 0.001 ampere/cm^2. This decrease in J is brought about by a temperature rise of the cathode from approximately 1,000°K (727°C) to approximately 1,430°K (1,157°C).

The curves of FIG. 3 show the changes in emission characteristics for pure tungsten and oxidized tungsten cathodes when operated in cesium vapor at 20°C and 80°C (a typical curve of a thorium-tungsten cathode is also shown). In many applications of this invention oxidized tungsten cathodes will be preferred to the foregoing described molybdenum cathodes due to the wider range of control available. FIG. 4 is a plot of emission characteristics, primarily over their negative temperature-emission characteristic ranges, of the elements Nobium (Nb), Tantalum (Ta), Molybdenum (Mo), Rhenium (Re), and Tungsten (W), and a 50—50 by weight molybdenum tungsten cathode all in cesium vapor at a T_{CS} of 200°C. These curves show the suita-

bility of these various elemental cathodes and the Mo-W cathodes for use in this invention.

An example of another embodiment of the invention uses an oxidized tungsten cathode in cesium vapor. (Specific structure will be set forth later.) In this embodiment the reservoir temperature of the cesium T_{CS} is 293°K (20°C). From the foregoing characteristics $(dJ/J)/dT$ has a mean straight line characteristic of approximately -3.2×10^4 $°K/T^2$ and the corresponding range of J is from approximately 0.1 ampere/cm² to approximately 10^{-5} ampere/cm², which may be used. This involves a temperature rise from approximately 950°K (677°C) to approximately 1,200°K (927°C). The cesium vapor pressure p_{CS} (at $T_{CS}=20°C$) is approximately 10^{-6} Torr with a cesium density n_{CS} somewhat less than $10^{11}/cm^3$. This is essentially only a trace amount of cesium relative to the working gas (such as Argon, Neon or Xenon) which conventionally are at nominal pressures of approximately 1 Torr. Operation at higher current densities such as 1 ampere/cm² may be obtained by increasing the cesium reservoir temperature to approximately 40°C.

It is to be observed that the presence of adsorbed cesium lowers the work function of the cathode and that the higher the work function of a material before adsorption the lower the work function is after adsorption. For example:

Metal	Work function bare metal	Work function after Cs adsorption
Nb	4.0	2.5
Mo	4.2	2.1
W	4.6	2.0
R_e	5.0	1.8

The lower the work function, obviously, the higher the electron emission. The elemental cathodes with cesium have the advantage of being rugged and self-healing from accidental overloads. The complex cathodes that generally have a higher work function than the elemental cathodes when not in the presence of cesium, likewise, generally have a lower work function with adsorbed cesium. The complex cathodes are not as rugged as the elemental cathodes and should be protected (by proper electrical operation) against excessive sputtering to prolong their useful life. They have utility for the lower excitation values and intensities required by many molecular gas systems and lasers.

FIG. 5 is a pictorial-schematic diagram of an embodiment of a transverse discharge gaseous laser with a flat cathode having the structure taught by this disclosure. The lasing gas enclosure **51** with Brewster windows **52** and **53** is conventional and well known in the art. Likewise, well known is the positioning in the optical cavity between conventional laser mirrors **54** and **55**, one of which conventionally is partially reflective or has an aperture for release of laser energy from the cavity. The gas to be lased from container **56** is admitted by valve **57**. The enclosed volume is evacuated by a pump connected to line **58** and pressure controlled by valve **59**. This plumbing is well known in the art. A variable voltage source **60** provides the discharge potential between the anode **61** and the cathode **62**. The cesium adsorbing cathode **62** is indirectly heated by the heater **63**, whose temperature is controlled by the variable voltage **64**. In addition to the conventional tube **65** communicating with the laser chamber, another tube **66** terminating in a closed reservoir chamber **67** is provided. This reservoir **67** is partially filled with cesium and it is contained in temperature bath **68** in the vessel **69**. The temperature of the temperature bath is conventionally controlled by the heat exchanger **70**. The temperature of the temperature bath determines the temperature of the cesium in the reservoir and hence the cesium vapor pressure within the laser. The discharge voltage source **60**, the cathode temperature (by adjustable voltage **64**), and the cesium vapor pressure (by heat exchanger **70**), are all variable, and by the foregoing teaching container herein, with the proper cesium adsorbing cathode as also taught herein, the emission from the cathode will be stabilized and optimized energy provided the electrons entering the plasma of the lasing gas used. Examples of specific cathode materials, gases, cesium vapors pressures, cathode temperatures, and discharge voltages have previously been enumerated.

FIG. 7 is a pictorial-schematic diagram of an embodiment of a slotted hollow cathode transverse discharge gaseous laser incorporating the improvements of this invention. In this embodiment the anode is a circular metal tube **71**. The circular slotted hollow cathode **72** is surrounded by the heater **73**. The laser tube has conventional Brewster windows **74** and **75**, and is positioned in an optical cavity between conventional laser mirrors **76** and **77**. Cesium vapor is admitted to the laser volume from reservoir **78** through tube **79**. The cesium vapor pressure is controlled by the heat exchanger **80**. FIG. 8 is a section view showing the representative cathode, anode, and heater structure. The advantages of the slotted hollow cathode are well known, adequately contained in previously referenced material, and need not be further described here. It is the improvement, as previously described, of using a thermionic cathode in cesium vapor to obtain a stabilized electron emission at an optimized energy content that this disclosure is primarily concerned with.

FIG. 9 is a pictorial-schematic representation of an embodiment of a plasma analysis or diagnostic system incorporating this invention. It is very desirable to know the selective excitation of atomic and molecular levels of plasma substances in order to investigate their structure and the nature of intensities of the spectrum of radiation. Resonance effects at various energy levels are necessary pieces of information in utilizing the plasma (such as for laser). The structure shown in FIG. 9 is similar to that of FIG. 5 except FIG. 5 is a laser, FIG. 9 is not a laser. No optical cavity is used on the apparatus of FIG. 9 and no buildup of lasing action occurs. The gas to be analyzed from container **91** is monitored into the discharge tube under controlled pressures. A plasma is formed in the gas between the anode **93** and the cesium adsorbing thermionic cathode **94**. The characteristics of the plasma are observed through the conventional Brewster windows **95** and **96** by conventional optical diagnostic instrumentation **101**. Typical of such instrumentation is the dual-beam spectrometer system shown on page 205 of "Laser Technology and Applications" by S. L. Marshall, McGraw-Hill (1968). The thermionic cathode **94** is operated at various determined temperatures by the adjacent heat exchanger **97** to either heat or cool the cathode through the external heat exchanger **98**. In

some instances due to the heat from the plasma and ions heating the cathode, it is necessary to cool the cathode in order for it to operate at the determined temperature. Thus, the conventional electric heater normally used to heat the cathode is replaced by small tubes through which a conventional heating or cooling medium, such as liquid gallium, at the desired temperature is pumped. In some embodiments of the previously described lasers, particularly those employing high energy plasmas it is necessary to also cool the thermionic cathode in a similar manner to obtain the desired cathode temperature, particularly after operation has been started with a heated cathode. The discharge potential is controlled by the variable voltage source **99**, and the cesium vapor pressure controlled by the heat exchanger **100** as in the previous embodiments. In all embodiments of this invention it is desirable that no part of the closed gas system be operated at a temperature lower than that of the cesium bath, otherwise cesium will settle out of the vapor on the cooler surface or surfaces. Particularly is it important that this not happen on the Brewster windows. Hence, in some embodiments it is desirable to operate the complete system at a temperature slightly higher than that of the cesium pool, (in which case it may be necessary to cool the cesium pool) or at least maintain the temperature of the Brewster window, or windows, above that of the cesium reservoir. Such a tool for the diagnostic study of plasmas as represented by FIGS. **9** and **10** has not heretofore been available.

Generally, in many instances, as shown in FIGS. **3** and **4**, the cesium pool may be operated at room temperatures (20°C) with oxide cathodes, and at a nominal 200°C cesium pool temperature with the elemental cathodes. The distinction between the conventional "cold cathode" and the "hot" or thermionic cathode should be noted. In the cold cathode the electron emission is drawn from the cathode by the electric field while in the thermionic cathode the electron emission occurs because of the temperature or heat of the cathode. Thus, even though a thermionic cathode in a particular instance is cooled, electron emission from the cathode still takes place because of the temperature of the cathode and is relatively independent of the electric field. Additional description of "hot" and "cold" cathodes may be found in "Electronic Designers' Handbook" by R. W. Landee, D. C. Davis, and A. P. Albrecht, McGraw-Hill (1957) at pages 2–49 through 2–57.

I claim:

1. The improvement in a DC, transverse discharge, gaseous, slotted hollow cathode laser, comprising:

a. a reservoir communicating with the interior of the said laser;

b. elemental cesium positioned in the said reservoir;

c. the said slotted hollow cathode fabricated from a cesium adsorbing thermionically emitting material;

d. means for thermionically positioning the said cathode within a determined temperature range to provide an emission current density inversely related to the temperature of the said cathode.

2. The improvement in a DC, transverse discharge, gaseous, laser comprising:

a. a cesium adsorbing thermionic cathode positioned within the said laser;

b. a source of cesium vapor within the said laser; and

c. means for maintaining the said thermionic cathode at a predetermined temperature to provide thermionic emission current from the said cathode that is inversely related to the temperature of the cathode.

3. The improvement as claimed in claim **2** wherein the said thermionic cathode is fabricated from oxidized tungsten.

4. The improvement as claimed in claim **2** wherein the said thermionic cathode is fabricated from molybdenum.

5. The improvement in an argon ion, DC, transverse discharge, gaseous laser having a lasing medium between a cathode and an anode, the said improvement comprising:

a. the said cathode fabricated from molybdenum for providing thermionic emission;

b. a source of cesium within the said laser; and

c. means for thermally positioning the said cathode to a temperature such that the thermionic emission from the cathode is inversely related to the temperature of the cathode.

6. The improvement as claimed in claim **5** wherein the said means for thermally positioning the cathode is an electrically activated heater positioned adjacent the said cathode.

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