June 25, 1968 C. W. HANKS 3,390,249

VAPORIZATION MONITORING APPARATUS

Filed Sept. 20, 1965

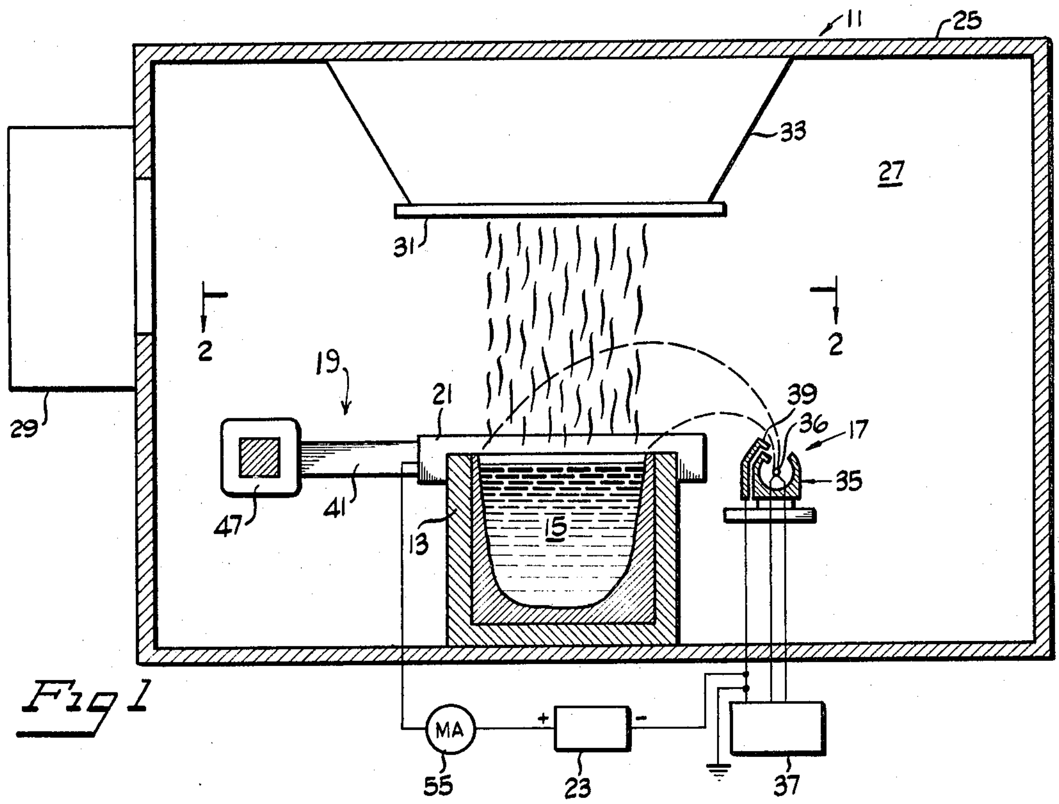


Fig 1

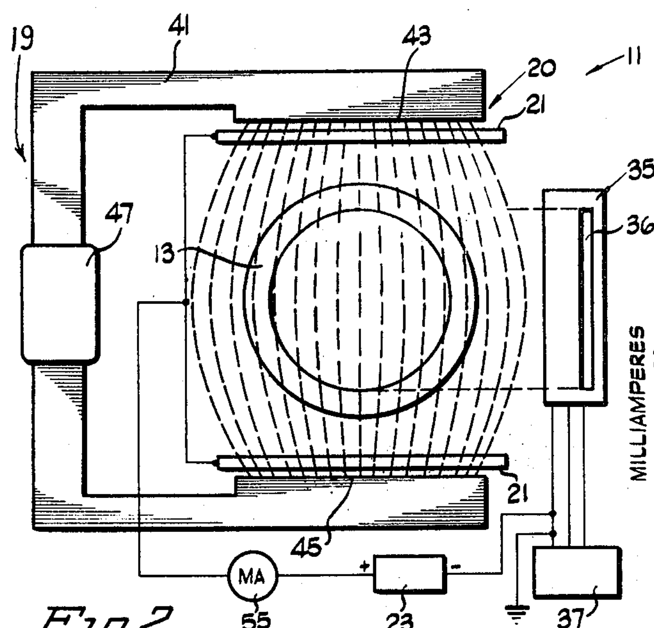
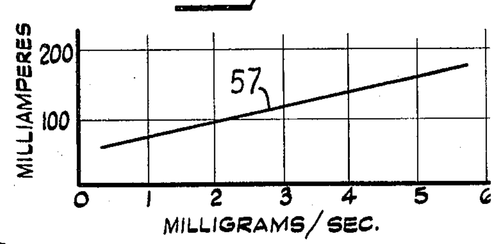


Fig 2

Fig 3



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VAPORIZATION MONITORING APPARATUS

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ABSTRACT OF THE DISCLOSURE

A vaporization monitor provides an indication of the density of the vapor cloud above the evaporant in an electron beam furnace by collecting the low velocity ionization electrons which are constrained from passing to the evaporant by the magnetic focusing field.

This invention relates geenrally to an apparatus for monitoring the operation of a vaporization furnace and more particularly it relates to an apparatus for measuring the vapor density within an electron beam vaporization furnace.

The present invention is particularly adapted for use with electron beam furnaces wherein an evaporant is vaporized by electron beam bombardment. Such a vaporization furnace generally includes a crucible constructed of inert material mounted within an evacuated enclosure. The evaporant, typically a metallic substance is positioned within the crucible and heated therein by a high intensity electron beam.

The electron beam is often generated by a low beam source positioned below the opening of the crucible thereby protecting it from the vapors generated within the crucible. The electron beam so generated is directed by a curved transverse magnetic field which bends the electrons over and down into the crucible. An electron beam furnace utilizing a magnetically directed low beam source is described in my Patent No. 3,177,535 issued Apr. 13, 1965.

The density of the vapor cloud emitted from the crucible is particularly critical in that it materially affects the rate of deposition of evaporant upon the substrate. It is therefore advantageous to provide a means of continuously evaluating the density of the vapor cloud within the vaporization furnace. Heretofore an economical, convenient apparatus for so monitoring vapor density within a vaporization furnace has been generally unavailable. The density of the vapor cloud is generally a function of the intensity of the electron beam, the rate of evaporant feed and other lesser variables.

A main object of the present invention is to provide an improved apparatus for monitoring vapor density. A more particular object is to provide an improved means of monitoring the vapor density within a vaporization furnace. A further object is to provide an improved apparatus for monitoring the vapor density within an electron beam vaporization furnace, and a still further object is to provide a vapor density monitoring apparatus which includes a means for collecting secondary electrons and a means for utilizing said electrons to obtain an indication of the vapor density within the vaporization furnace.

Other objects and advantages of this invention will become apparent through reference to the following description and accompanying drawings which show an illustrative embodiment of this invention.

FIGURE 1 is an illustration, partly in section and partly diagrammatic, of an electron beam furnace including certain features of this invention;

FIGURE 2 is a sectional view, also partly diagrammatic, showing the electron beam furnace of FIGURE 1 and taken along line 2—2 of FIGURE 1; and

FIGURE 3 is a graphical representation of the operational characteristics of an embodiment of this invention.

Briefly, the vaporization monitor of the present invention is particularly adapted for use with an electron beam vaporization furnace **11**. The furnace **11** includes a crucible **13** containing an evaporant **15** such as copper.

To heat the evaporant **15** an electron beam generator **17** is provided for generating a high intensity electron beam. The electron beam so generated is directed into the crucible **13** by a magnetic focusing means **19**. A vapor monitoring means **20** which comprises at least one electrically conductive member **21** positioned adjacent the focusing means **19** is provided. A power supply **23** applies a positive voltage to the members **21** so that when the furnace **11** is in operation electrons will flow to and through the conductive members **21**. The electron flow so produced has a functional relation to the vaporization rate of the evaporant **15** within the furnace **11**.

More particularly, the electron beam furnace **11** illustrated in FIGURE 1 is contained within an enclosure **25** defining a chamber **27** therein. To reduce the pressure within the chamber **27** to facilitate coating, a vacuum pump **29** is provided which communicates through the wall of the enclosure **25**. The pump **29** serves to evacuate the chamber continuously so that a high vacuum of the order of 1 micron of mercury may be maintained therein. A substrate **31** is positioned within the enclosure **25** upon a suitable platform **33** secured to the uppermost wall of the enclosure.

The crucible **13** is positioned within the chamber **27** so that evaporant vapors emitting from the crucible will be deposited upon the substrate **31**. The crucible **13** may be constructed of inert material and the outer surface thereof water cooled to prevent reaction of the crucible with the heated evaporant **15** maintained therein.

The evaporant **15** is vaporized by the electron beam generated by the high intensity electron beam generator **17**. In accordance with the illustrated embodiment, the electron beam generator **17** includes an electron gun **35**. The electron gun generally includes an electron emitting surface **36** which may be in the form of a directly or indirectly heated cathode which, in the illustrated embodiment, is energized by a suitable power supply **37**. The electron so produced are accelerated to high velocity by an anode **39** which is positively with respect to the cathode and directed in a beam towards the crucible **13**. The anode **39** may be energized by another connection to the power supply **37**. The electrons produced by the electron gun **35** will hereafter be referred to as primary electrons. As shown in FIGURE 1 the electron gun is positioned below the opening of the container thereby assuring minimum contact with the vapors evolved from the crucible **13**.

The magnetic focusing means **19** is positioned with respect to the crucible **13** to direct the beam of primary electrons over the edge of the crucible and onto the evaporant **15** therein. The means **19** produces a magnetic field which spans the open end of the crucible **13** and which is transverse to the direction of the electron beam. The means **19** includes a ferromagnetic horseshoe-shaped core

41 having opposing pole faces 43 and 45. The illustrated core is rectangular in cross section; however, other core configurations may be used in accordance with this invention. A coil 47 is wound about the central portion of the core 41. The coil 47 is supplied with direct current from a suitable power supply (not shown) so that a magnetic field will be produced between the pole faces 43 and 45. As previously mentioned, the pole faces of the core are positioned so that the magnetic field so generated will span the open end of the crucible 13.

In the illustrated embodiment the conductive members 21 of the monitoring means 20 are in the form of a pair of rectangular electrically conductive plates. The conductive plates 21 are preferably constructed of non-magnetic material capable of withstanding the heat generated by the vaporization furnace 11. Plates constructed of tungsten or tantalum have been found satisfactory for this application. The plates must be electrically conductive, however, it is preferred that the plate material be such that the magnetic flux lines will pass therethrough substantially unaffected. The plates 21 are generally rectangular in shape and are slightly larger than the pole faces 43 and 45. As shown in FIGURE 2 each plate 21 is positioned parallel to and slightly spaced from the respective pole faces 43, 45, and are supported thereon by suitable insulators. While the illustrated embodiment provides two conductive plates each positioned parallel to the pole faces of the core, an alternative embodiment may utilize one or more plates; alternatively, the core 41 may be suitably insulated from the surrounding apparatus and the pole faces 43 and 45 utilized in lieu of electrically conductive plates.

To facilitate the collection of electrons from the plates 21 a direct current power supply 23 is provided which applies a positive voltage to the plates with respect to ground. In accordance with the illustrated embodiment the power supply 23 provides a positive potential from a fraction of a volt up to more than the ionizing potential of the vapor atoms. The negative terminal of the power supply 23 is secured to ground. An indicating means 55, in the form of a direct current milliammeter, is connected between the power supply 23 and the plates 21 as illustrated in FIGURES 1 and 2.

In operation, the substrate 31 is secured to the platform 33 in alignment with the open end of the crucible 13. The evaporant 15 is placed within the crucible, and the electron beam generator 17 is energized by means of the power supply 37. Direct current is simultaneously supplied to the coil 47, thereby producing a magnetic field across the open end of the crucible. The transverse magnetic field so generated bends the primary electron beam over the edge of the crucible 13 onto the evaporant thus producing a vapor cloud above the crucible which rises through the enclosure 25 and is thus continuously deposited upon the substrate 31.

Before proceeding with a discussion of the operation of the monitoring means 20, the physical effects of a magnetic field upon an electron will now be considered. When an electron is directed into a uniform magnetic field parallel to the lines of flux thereof, the path of such electron will not be altered by the presence of the field and the electron will generally follow along the lines of magnetic flux. If the electron enters the magnetic field on a path perpendicular to the uniform field, its path will be altered to a circle. The radius of the circle is a function of the velocity of the electron and the intensity of the magnetic field. The primary electrons from the gun 35 enter the magnetic field at such high speed that their trajectory is shaped to that of an arc rather than a complete circle. However, slower moving electrons having an energy the order of 100 electron volts entering into a magnetic flux density of 200 gauss will travel in a circular path having a radius of curvature of about 1.69 millimeters. In the event an electron is introduced into the magnetic field in a path having both parallel and perpendicular components to the flux lines the path of the electron within the field will be in the form of a helix with the central axis thereof parallel to the lines of flux.

In connection with the operation of the monitoring means 20, as the primary electrons generated by the electron gun 35 pass into the dense vapor cloud above the crucible 13 a small percentage of the neutral vapor atoms will become ionized by the inelastic collision between the neutral vapor atoms and the primary electrons. The vapor ions thus produced will exhibit very little change in their energy content as a result of this collision because of their large mass as compared to that of the impacting primary electron. The electrons released, hereinafter referred to as secondary electrons, from the neutral vapor atoms by the colliding primary electrons will nearly always receive some kinetic energy of from zero volts to perhaps thousands of volts more than needed for release from the individual vapor atoms. Since the secondary electrons are slower moving than the primary electrons, the magnetic flux keeps them within the cloud for a longer period of time and they are therefore more effective in producing further ionization of other neutral vapor atoms than the primary electrons. Thus, a chain reaction is set up within the vapor cloud.

The secondary electrons are released from the atoms in all possible directions from perpendicular to parallel to the magnetic lines of flux. As a result of the small radius of curvature of the secondary electrons it is impossible for them to escape from the magnetic field in a direction perpendicular to the field lines and they are entrapped or constrained with respect to this direction so that they cannot pass to the evaporant. Thus, the secondary electrons move in spirals whose net direction is parallel to the field lines and, consequently, they impinge on the plates 21. This spiraling motion of the released electrons provides a longer path length and thus a much greater chance for more ionizing collisions before the electrons reach the plates 21.

To aid in the collection of electrons a positive potential is applied to the conductive plates 21 positioned generally transverse to and adjacent the pole pieces 43 and 45 which may be from a fraction of a volt up to more than the ionizing potential of the vapor atoms. By increasing the voltage to several times that of the ionizing potential, an amplification is achieved that can be several orders of magnitude higher than the primary electron current. By placing the conducting plates 21 at each end of the magnetic field the released electrons will be collected thereupon as they move out of the vapor cloud along the lines of the magnetic field. The electrons collected upon the plates 21 will flow through the milliammeter 55. The meter deflection will generally be proportional to the intensity of the vapor cloud within the enclosure.

The calibration of the milliammeter 55 is best determined empirically for the particular system in use. In this regard, it is advisable to make controlled evaporation runs to relate the current collected on the plates 21 to measured evaporation or deposition rates. Once the relationship is determined, it is necessary merely to adjust the intensity of the gun 35 or the evaporant feed rate to the desired meter reading to obtain the required evaporation or deposition rate.

A typical empirically obtained calibration curve is displayed in FIGURE 3. The furnace used in obtaining this curve included a one inch diameter carbon crucible having a copper evaporant therein. A 5 kilovolt electron beam having a 100 milliampere current was utilized to vaporize the evaporant. The conductive plates were maintained at a positive potential of approximately one hundred volts. The curve 57 illustrated in FIGURE 3 shows the relationship between plate current (graphical ordinate) and evaporant coating per unit time (graphical abscissa) for the particular furnace under test.

Although but one specific embodiment of this invention has been herein shown and described, it will be understood that details of the construction shown may be altered without departing from the spirit of this invention as defined by the following claims.

What is claimed is:

1. A vaporization monitor for use with an electron beam vaporization furnace which includes a crucible having an evaporant therein, means for generating a high intensity electron beam of high velocity electrons, and means for providing a magnetic field oriented generally transverse to the beam for directing said electron beam into the crucible for vaporizing the evaporant therein and producing a vapor cloud thereabove, said means for providing a magnetic field constraining relatively low velocity electrons produced by ionization of the vapor cloud in the space above the crucible from passing to the evaporant, said monitor comprising means for collecting only said relatively low velocity electrons, and means coupled to said collecting means and responsive to the rate at which such electrons are collected to provide an indication of the density of the vapor cloud above the crucible.

2. A vaporization monitor for use with an electron beam vaporization furnace which includes a crucible having an evaporant therein, means for generating a high intensity electron beam of high velocity electrons, and magnetic focusing means directing said electron beam into said crucible for vaporizing the evaporant therein and producing a vapor cloud above said crucible, said magnetic focusing means constraining only relatively low velocity electrons produced by ionization of the vapor cloud in the space above the crucible from passing to the evaporant, said monitor comprising an electrically conductive member positioned generally transverse to the magnetic field produced by said magnetic focusing means and adjacent the region of the vapor cloud and means for applying a direct current potential to said conductive member, the current flowing through said conductive member being indicative of the vapor density of the vapor cloud above the crucible.

3. A vaporization monitor for deriving an indication of the vapor density of an evaporant produced by electron beam heating wherein a magnetic field producing means is provided for directing the electron beam onto the evaporant and producing a vapor cloud thereabove, the interaction of the electron beam with the vapor cloud producing ionization of the vapor atoms and emission of electrons having velocities substantially less than those of the primary electrons, said magnetic field producing means constraining said low velocity electrons from passing to the evaporant but passing the high velocity electrons thereto, said monitor comprising electron collecting means adjacent the vapor cloud for collecting only the low velocity electrons, and means coupled to said collecting means and responsive to the rate at which such electrons are collected to provide an indication of the density of the vapor cloud.

4. An electron beam vaporization furnace that includes an open mouth crucible disposed in an evacuated chamber, means for generating a high intensity beam of primary electrons within said chamber, and magnetic means for generating a magnetic field within said chamber transversely through the path of said electron beam to direct the path of said beam into said crucible for vaporizing the evaporant from the open mouth thereof, a vapor density monitor comprising an electrode disposed generally transverse to said magnetic field within the chamber out of the path of said beam, direct current power supply means coupled to said electrode to apply a relatively positive potential thereto, including means for utilizing the electron current collected at said electrode as an indication of the vapor density of the evaporant emitted from said crucible.

5. A vaporization monitor for use with an electron beam vaporization furnace which includes a crucible having an evaporant therein, means for generating a high intensity electron beam, and focusing means providing a magnetic field across the crucible for directing said electron beam into said crucible and vaporizing the evaporant therein to produce a vapor cloud above said crucible, said monitor comprising an electrically conductive member positioned generally transversely to the magnetic field and adjacent said magnetic focusing means, a direct current power supply connected to said conductive member, and utilizing means associated with said power supply whereby the current flowing through said power supply is related to the vapor density above said crucible.

6. A vaporization monitor for use with an electron beam vaporization furnace which includes a crucible having an evaporant therein, an electron gun for generating a high intensity electron beam, and a magnetic focusing means for directing said electron beam into said crucible for vaporizing the evaporant therein to produce a vapor cloud above said crucible said magnetic focusing means having two opposing pole faces between which a magnetic field is maintained, said monitor comprising at least one non-magnetic electrically conductive plate placed within said magnetic field and positioned adjacent said pole faces and a power supply connected to said conductive plate for applying a voltage thereto whereby the current flowing through said power supply is related to the vapor density of said evaporant above said crucible.

7. A vaporization monitor for use with an electron beam vaporization furnace which includes a crucible having an evaporant therein, an electron gun for generating a high intensity electron beam and a magnetic focusing means for directing said electron beam into said crucible for vaporizing the evaporant therein to produce a vapor cloud above said crucible, said magnetic focusing means having two opposing pole faces between which a magnetic field is maintained, said monitor comprising at least one non-magnetic electrically conductive electrode positioned adjacent at least one of said pole faces within said magnetic field, a direct current power supply the positive terminal of which is connected to said electrode for applying a positive voltage thereto and an indicating means connected in series with said electrode and said power supply to indicate the magnitude of the electron current flowing to said electrode.

8. A vaporization monitor for use with an electron beam vaporization furnace which includes a crucible having an evaporant therein, an electron gun for generating a high intensity electron beam, and a magnetic focusing means for directing said electron beam into said crucible for vaporizing the evaporant therein to produce a vapor cloud above said crucible, said magnetic focusing means having opposing pole faces thereof positioned adjacent said crucible to provide a magnetic field across the opening thereof, said monitor comprising at least one non-magnetic electrically conductive plate positioned adjacent at least one of said pole faces within said magnetic field, a direct current power supply, the positive terminal of which is connected to said plate, for applying a positive voltage thereto, and a meter connected in series with said plate and said power supply to indicate the magnitude of the electron current flowing to said plate.

9. A vaporization monitor for use with an electron beam vaporization furnace which includes a crucible having an evaporant therein, an electron gun for generating a high intensity electron beam, and a magnetic focusing means including a core for directing said electron beam into said crucible for vaporizing the evaporant therein, said core of said magnetic focusing means having two opposing pole faces positioned adjacent the sides of said crucible to provide a magnetic field across the opening thereof, said monitor comprising a direct current power supply connected to said core of said magnetic focusing means and an indicating means connected in series with said power supply and said core to indicate the electron flow through said power supply.

10. A vaporization monitor for use with an electron beam vaporization furnace which includes a crucible having an evaporant therein, an electron gun for generating a high intensity electron beam, and an electromagnetic focusing means for directing said electron beam into said crucible for vaporizing the evaporant therein, to produce a vapor cloud above said crucible, said electromagnetic focusing means having a core with two opposing pole faces, said pole faces positioned adjacent said crucible to provide a magnetic field across the opening thereof, said monitor comprising a pair of electrically conductive plates disposed generally parallel to said pole faces, a direct current power supply, the positive terminal of which is connected to said plates, and a direct current meter

associated with said power supply to indicate the current flowing therethrough.

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