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3,404,084

APPARATUS FOR DEPOSITING IONIZED ELECTRON BEAM EVAPORATED MATERIAL ON A NEGATIVELY BIASED SUBSTRATE

Filed Oct. 20, 1965

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VARIABLE VOLTAGE SOURCE

CATHODE POWER SUPPLY

VACUUM PUMP

FIG. 2
APPARATUS FOR DEPOSITING IONIZED ELECTRON BEAM EVAPORATED MATERIAL ON A NEGATIVELY BIASED SUBSTRATE

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Filed Oct. 20, 1965, Ser. No. 498,958
6 Claims. (Cl. 204—298)

This invention relates to coating apparatus, and more particularly to a novel and improved vacuum apparatus in which a substrate surface may be simultaneously cleaned and coated by bombardment with ions of the material to be deposited upon the substrate surface.

To achieve a strongly adherent film by vacuum deposition it is necessary that the surface of the substrate be free from all contaminants at the instant of deposition. Elaborate chemical and physical cleaning procedures have generally been required to achieve this condition. Recently, however, systems have been developed which are capable of simultaneously depositing a coating and ion cleaning to prevent contaminants from collecting upon the substrate surface. While these deposition processes provide adequate cleaning capabilities and adherent properties of the deposited film, they are limited to the deposition of film material that can be evaporated by the usual electrical filament heating process. Thus, these processes are generally restricted to the deposition of non-refractory metals, and materials such as tungsten, molybdenum, quartz and high temperature ceramics cannot be readily evaporated and deposited upon a substrate by these processes.

In the present invention free electrons emitted from a hot cathode are magnetically condensed, or focused, into a very narrow and intensive beam which is directed against only a small portion of the surface of the charge of coating material to be evaporated. This very intense electron beam produces sufficient heat to vaporize even the most highly refractory materials.

Briefly described, the invention comprises a means for magnetically focusing a very intense electron beam against the surface of a charge of coating material to produce an intense heat, whereby vapors of the charge are released by bombardment with the incoming electrons. A substrate to be simultaneously cleaned and coated is positioned between the ion source and an electrode to which is applied an electrical potential sufficient to accelerate the ions against the surface of the substrate. These accelerated ions will, because of their energy, simultaneously clean the substrate surface and become deposited thereon. A small portion of the ions that condense upon the surface of the substrate will be sputtered away by the bombardment of subsequent ions, while the remainder adhere to coat the substrate surface.

One embodiment of the invention comprises a vacuum chamber containing a tubular magnet, a circular cathode element disposed within the bore and adjacent one end of said magnet, and a charge container, or crucible, also disposed within the bore of the magnet and spaced from the cathode element. The crucible is connected as an anode so that electrons emitted from the cathode are accelerated toward the crucible and the charge material contained therein. The crucible is physically aligned within the magnet bore so that the intense field of the magnet will condense or focus the electron beam only against a portion of the surface of the charge material. The very intense heat produced by this very thin and intense electron beam will vaporize the portion of the charge surface that is struck by the electron beam. A relatively large percentage of the vaporized charge will readily become ionized when bombarded with incoming electrons and the ions are accelerated back through the circular cathode and against the surface of a substrate material which is supported by a suitably polarized electrode positioned outside of the bore of the magnet and generally in a line extending from the anode crucible along the center line of the magnet bore.

Another embodiment of the invention comprises a vacuum chamber containing a tubular magnet, a circular cathode element disposed within the bore and adjacent one end of the magnet, and a rod-shaped charge adaptably disposed within the bore of the magnet and spaced from the cathode element. In this embodiment the rod of charge material is coupled to an anode electrode which accelerates the electrons emitted from the cathode toward the rod of charge material. This embodiment is of particular value in those cases where it would be desirable to continually feed the charge material into the intense electron beam in order to obtain great quantities of deposited material over extended periods of time.

In the drawings which illustrate embodiments of the invention;

FIGURE 1 is a section drawing illustrating one embodiment of the ion deposition and cleaning apparatus, and

FIGURE 2 is a section drawing illustrating another embodiment of the vacuum apparatus which is adapted to continuously feed a wire of the charge material into the focal point of the electron beam.

In the embodiment illustrated in FIGURE 1, a vacuum chamber 10 is, during operation, maintained at a vacuum in the order of 10⁻⁸ torr by a vacuum pump 12 which may be connected to vacuum chamber 10 through suitable vacuum pipe 14. While not critical, vacuum chamber 10 may have an inside diameter in the order of 8 inches and may be constructed of any suitable material capable of withstandng the forces exerted by the above indicated vacuum. Within vacuum chamber 10 is a tubular magnet 16 which is positioned so that the central longitudinal axis is substantially parallel with the longitudinal center line of vacuum chamber 10. Magnet 16 may have a length in the order of two inches, an outside diameter of approximately two inches, an inside bore diameter of approximately one inch, and is magnetically polarized to produce a longitudinal magnetic flux that emanates from one end, passes around the external and internal bore surfaces, and enters at the opposite end of magnet 16. Magnet 16 may either be a permanent or electromagnet, but should be of a type that will produce an extremely high flux field, since, in operation of the equipment illustrated, a magnetic flux density in the order of 40,000 gauss is desirable along the center line of the bore of magnet 16.

Within the bore and adjacent one end of magnet 16 is a circular cathode element 18, which may be constructed of tungsten wire, or a wire of any other material capable of suitable electron emission by the application of electrical current. Circular cathode 18 is positioned in a plane perpendicular to the center line of the bore of magnet 16, and is located within the flux field passing through the bore of magnet 16 so that it is located below the critical, or "turn-over," plane of the magnetic field. Cathode 18 may be connected by suitable conductors 20 through the wall of vacuum chamber 10 to a cathode power supply 23 that is capable of supplying power to heat cathode 18 to a point where it emits a high density of free electrons. If vacuum chamber 10 is constructed of a conductive material, the cathode conductors 20 should be insulated from vacuum chamber 10 by a feed-through insulator 22, which may be inserted in the wall of vacuum chamber 10 to prevent air leakage and destruction of the vacuum within the chamber.
When cathode 18 is heated and when the equipment illustrated in FIGURE 1 is in operation, a relatively high heat is generated in the general area around magnet 16. Since this heat may reach the Curie point of magnet 16, and thus may destroy the magnetic properties, magnet 16 should be surrounded, both externally and internally, with a coolant jacket 24 through which may be pumped a coolant, such as cold water, to maintain the temperature of the magnet well below the Curie point. Coolant jacket 24 must be constructed of a thin material having a relatively high heat conductivity, such as copper, and should be constructed so that it provides a sufficiently thick layer of coolant to maintain magnet 16 at a temperature below the Curie point.

Positioned within the bore of magnet 16 is a circular crucible 26 which is constructed of an electrically conductive material, such as copper, and which is electrically connected through the walls of vacuum chamber 10 by a suitable feed-through insulator 28 to a positive variable voltage power source 29, so that crucible 26 is connected as an anode to attract the electron flow emitted from cathode 18. The circular surface of crucible 26 that faces toward cathode 18 is indented, or concave, with the apex of the concave portion coincident with the center line of the bore of magnet 16. A charge of material to be evaporated 30 placed in crucible 26 will thus rest upon the center line of the longitudinal flux field within the bore of magnet 16. Since electron bombardment of the cathode 18 will heat charge 30, and therefore will heat crucible 26, the crucible must be cooled by an external coolant system. Therefore, crucible 26 should be provided with a coolant chamber 32, into which a coolant, such as cold water, may be supplied through a flexible and electrically insulating input pipe 34 arranged to supply the coolant to the area of crucible 26 which will be subjected to the electron bombardment from cathode 18. A flexible and electrically insulating output pipe 35 may be connected to any convenient portion of coolant chamber 32 for removing the warmed coolant from the coolant chamber 32.

While not essential to the operation of the invention, it is most advisable that crucible 26 be installed within the bore of magnet 16, so that it is adjustable along the length of the bore. The purpose of this adjustment of the crucible 26 is to provide the capability of adjusting the surface of the charge within crucible 26 to the region of maximum electron density, which, in general, is at the geometrical center of the bore of magnet 16. This adjustment may be accomplished with a rack and pinion assembly 38, in which the rack may be attached to coolant chamber 32 and the pinion gear connected through a suitably electrically insulated shaft 40 to an adjustment control that is external to vacuum chamber 10.

A substrate to be coated is mounted upon an electrically conductive substrate support 42 which is suspended within vacuum chamber 10 from an electrode 44 which extends through the end plate 46 of vacuum chamber 10 through a suitable feedthrough insulator 48. Although location is not critical, electrode 44 is preferably located on the center line of the cylindrical vacuum chamber 10 and along the extension of the center line of the bore of tubular magnet 16. Vacuum chamber 10 should be of sufficient size so that substrate 42 is positioned along said center line at distances varying between approximately 2 inches to 16 inches, or more, from cathode 18, and electrode 44 should therefore be adjustable within feedthrough insulator 48. While adjustment of the distance between cathode 18 and substrate support 42 is not necessary for the operation of the equipment, it is most desirable to provide flexibility of the equipment. Electrode 44 is connected to a variable voltage source 50, which, for flexibility, should be variable over a range of approximately +50 to -5000 volts. The reason for the desirability of a voltage that is variable over such a range is because experience has shown that certain materials may be deposited in films having different characteristics, depending upon the acceleration voltage, and hence the ion energy, applied to the substrate support 42. The physical and chemical properties of films produced by this equipment are dependent upon the energy of the ions arriving at the substrate surface.

FIGURE 2 illustrates another embodiment of the invention in which the charge may be in the form of a rod, or wire, which is continually fed into the very intense electron beam. This embodiment is particularly useful when it is desired to ion clean and deposit over an extended period of time. In such cases there may be a danger of evaporating the entire charge 30 within crucible 26, at which time the material forming crucible 26 may become vaporized and contaminate the deposit upon the surface of the substrate. In FIGURE 2 it will be noted that vacuum chamber 10 has been inverted so that substrate support 42 appears at the bottom of vacuum chamber 10 and magnet 16, along with cathode 18, are positioned at the top end of vacuum chamber 10. The charge material to be evaporated is in the form of a rod 52 which extends through the end plate 46 of vacuum chamber 10 through a suitable insulator 54, which is designed to electrically insulate rod 52 from vacuum chamber 10 and must also provide adequate sealing to prevent destruction of the vacuum within chamber 10. Some means must be provided to mechanically control the position of the end of the rod relative to the centroid of the magnet, as discussed previously in connection with the crucible implementation. That is, the end of rod 52 that extends within vacuum chamber 10 must be positioned so that it is aligned along the center line of the bore of magnet 16 and may be moved so that in operation a molten globule 58 formed at the end of rod 52 is located at the focal point of the electron beam emitted from cathode 18 and condensed by the flux action of magnet 16.

In order to prevent rod 52 from overheating along its length and to prevent the feedthrough insulator 54 from becoming damaged by the heating of rod 52, a coolant chamber 56 should surround rod 52. Coolant chamber 56 may also be positioned adjacent insulator 54 to prevent overheating.

While it is not necessary to invert vacuum chamber 10, as shown in FIGURE 2, it is desirable in order to take advantage of gravitational effects which tend to minimize the area of contact between the small globule 58 of molten charge that will develop at the end of charge material rod 52 and the coolant chamber 56. Thus, in the inverted condition, as shown in FIGURE 2, the electron beam emitted from cathode 18 and condensed by the flux field of the magnet 16 will bombard the tip of rod 52 to form a small molten globule 58. Thus, as the vaporization process continues and the molten globule 58 is vaporized and ionized, rod 52 may be advanced into the focal point of the electron beam to maintain a globule of adequate size and to insure a continuous supply of the charge material to be vaporized.

**Operation**

As previously discussed, care should be taken to assure that the substrate support 42 in FIGURE 1 and the end of rod 52 in FIGURE 2, is aligned upon the center line of the bore of magnet 16. This exact positioning is necessary because the electrons emitted from cathode 18 are funneled, or focussed, upon the center line by the strong magnetic flux action of magnet 16. The strong magnetic flux emanating from magnet 16 and entering the opposite end, will produce a magnetic flux condit along the center line of the bore of magnet 16, and will minimize the coulomb spreading of the electron beam. Electrons emanating from cathode 18 will therefore assume a funnel-shaped path and at the geometrical center of the bore of magnet 16 will be condensed into a
path of approximately 0.010 inch in diameter. Because the entire electron flow from cathode 18 is thus concentrated into such a narrow magnetic conduit, there is an extremely high electron density, which, in operation, may reach the value of $10^4$ electrons per cubic centimeter.

An ion cleaning and deposition process is initiated by first mounting the desired substrate to substrate support 42, placing the desired charge 30 in crucible 26 and evacuating vacuum chamber 10 to a pressure of between $10^{-4}$ and $10^{-5}$ torr. Crucible 26 is adjusted by rack and pinion assembly so that the surface of charge 30 is located at the point of highest electronic concentration, generally at the geometrical center of the bore of magnet 16, and a positive potential of approximately 30 volts is applied to crucible 26. When the cathode power supply 23 is energized to heat cathode 18, a flow of electrons will be emitted from the cathode 18, and, because crucible 26 is positive with respect to cathode 18, the electrons will be accelerated toward crucible 26. The intense magnetic field of magnet 16 will condense the electron flow so that electrons bombard only a small portion of the surface of charge 30. At this point it may be desirable, in order to rapidly start an arc, to bleed in a small supply of an inert gas, such as argon. This introduction of a small amount of inert gas will establish an arc immediately to start the vaporization of the charge material, and the flow of this inert gas may be stopped as soon as the electron bombardment of charge 30 initiates the vaporization of the charge. When vaporization of charge 30 is initiated, a gas is formed by the molecules of the charge and the electron beam will form a glow, or arc, within the gas of the charge. Once the vaporization process has initiated, the potential on crucible 26 may be increased to approximately 200 volts.

As the gas is released from the surface of charge 30 a relatively high vapor pressure is created in the immediate vicinity of the charge material, and the molecules, or atoms, are bombarded by the electrons from cathode 18 to knock off negative charges from the atoms thus creating positive ions of charge 30. The positive ions are directed back toward cathode 18 and because of the negative potential upon substrate support 42, the ions will pass through cathode 18 and will be accelerated against the surface of the substrate attached to substrate support 42.

Only a portion of the ions bombarding the substrate surface will adhere to the surface. A small portion will bombard the surface and will be released, or sputtered off. These non-adhering ions will effectively clean the surface of the substrate, so that during operation the substrate surface is being simultaneously ion cleaned and deposited with the ions of charge 30.

The operation of the embodiment illustrated in FIGURE 2 is identical with the operation of the embodiment in FIGURE 1. In FIGURE 2, electrons emitted from cathode 18 are focussed by the action of the magnetic flux of magnet 16, so that the highest concentration of electrons are at the geometrical center of the bore of magnet 16. Rod 52 is inserted into the bore of magnet 16 so that its end is located at the point of highest electron concentration. In operation, the electron beam will strike the end of rod 52, causing a melting into a tear-drop, or molten globule 58, a vaporization of the material, and an ionization of the vapor. As the material of rod 52 is vaporized, rod 52 may be further advanced into the chamber to provide a continuous source of charge.

What is claimed is:

1. An ion cleaning and deposition apparatus comprising:
   a. a vacuum chamber,
   b. pumping means for creating a vacuum within said chamber,
   c. a tubular magnet within said chamber, said magnet being magnetized to produce a longitudinal flux field within the bore of said magnet,
   d. a circular cathode element positioned within the bore of said magnet and perpendicular to the center line of said bore,
   e. electrical means coupled to said cathode element for heating said element wherein an electron flow is emitted from said element,
   f. an electrically conductive anode positioned within the bore of said magnet and spaced from said cathode element, the center of said anode being aligned so that a charge placed in said anode will be located upon the center line of said flux field,
   g. electrical means coupled to said anode for polarizing said anode with respect to said cathode element causing electron flow to be emitted by said cathode element and accelerated through the magnetic conduit produced by said flux field to the charge in said anode heating and vaporizing the surface of said charge and causing said vapors to be ionized by bombardment from said electron flow,
   h. adjustment means associated with said anode for adjusting the position of said charge along the center line of said flux field,
   i. a substrate support within said chamber and positioned externally of said bore of said magnet and substantially on a line extending from the center of said anode and through said circular cathode element to said support, and
   j. electrical means coupled to said substrate support for applying a variable potential to said support whereby a substrate may be bombarded with ions at a variable energy.

2. The apparatus of claim 1 wherein the mode comprises a crucible supporting the charge material.

3. An ion cleaning and deposition apparatus according to claim 1, including adjustment means associated with said substrate support for adjusting the position of a substrate along said line extending from the center of said crucible and through said cathode element.

4. An ion cleaning and deposition apparatus comprising:
   a. a vacuum chamber,
   b. pumping means for creating a vacuum within said chamber,
   c. a tubular magnet within said chamber, said magnet being magnetized to produce a longitudinal flux field within the bore of said magnet,
   d. a circular cathode element positioned within the bore of said magnet and perpendicular to the center line of said bore,
   e. electrical means coupled to said cathode element for heating said element wherein an electron flow is emitted from said element,
   f. anode means for supporting a charge of a desired material within the bore of said magnet and spaced from said cathode element, at least a portion of the surface of said charge being located upon the center line of said flux field,
   g. electrical means coupled to said anode for polarizing said anode with respect to said cathode element, causing electron flow to be emitted by said cathode element and accelerated through the magnetic conduit produced by said flux field to the charge in said anode, heating and vaporizing the surface of said charge, and causing said vapors to be ionized by bombardment from said electron flow,
   h. a substrate support within said chamber and positioned externally of said bore of said magnet and substantially on a line extending from the center of said crucible and through said circular cathode element to said substrate,
   i. electrical means coupled to said substrate support for applying a variable potential to said support whereby a substrate may be bombarded with ions at a variable energy.

5. An ion cleaning and deposition apparatus according...
to claim 4, including adjustment means associated with said anode means for adjusting said charge along the center line of said flux field.

6. An ion cleaning and deposition apparatus according to claim 4, including adjustment means associated with said substrate support for adjusting the position of said support along said line extending from the center of said crucible and through said cathode element.

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