

March 5, 1968

H. E. T. GOWEN
MEANS FOR CONTROLLED DEPOSITION AND GROWTH
OF POLYCRYSTALLINE FILMS IN A VACUUM

3,371,649

Original Filed Sept. 23, 1960

7 Sheets-Sheet 1

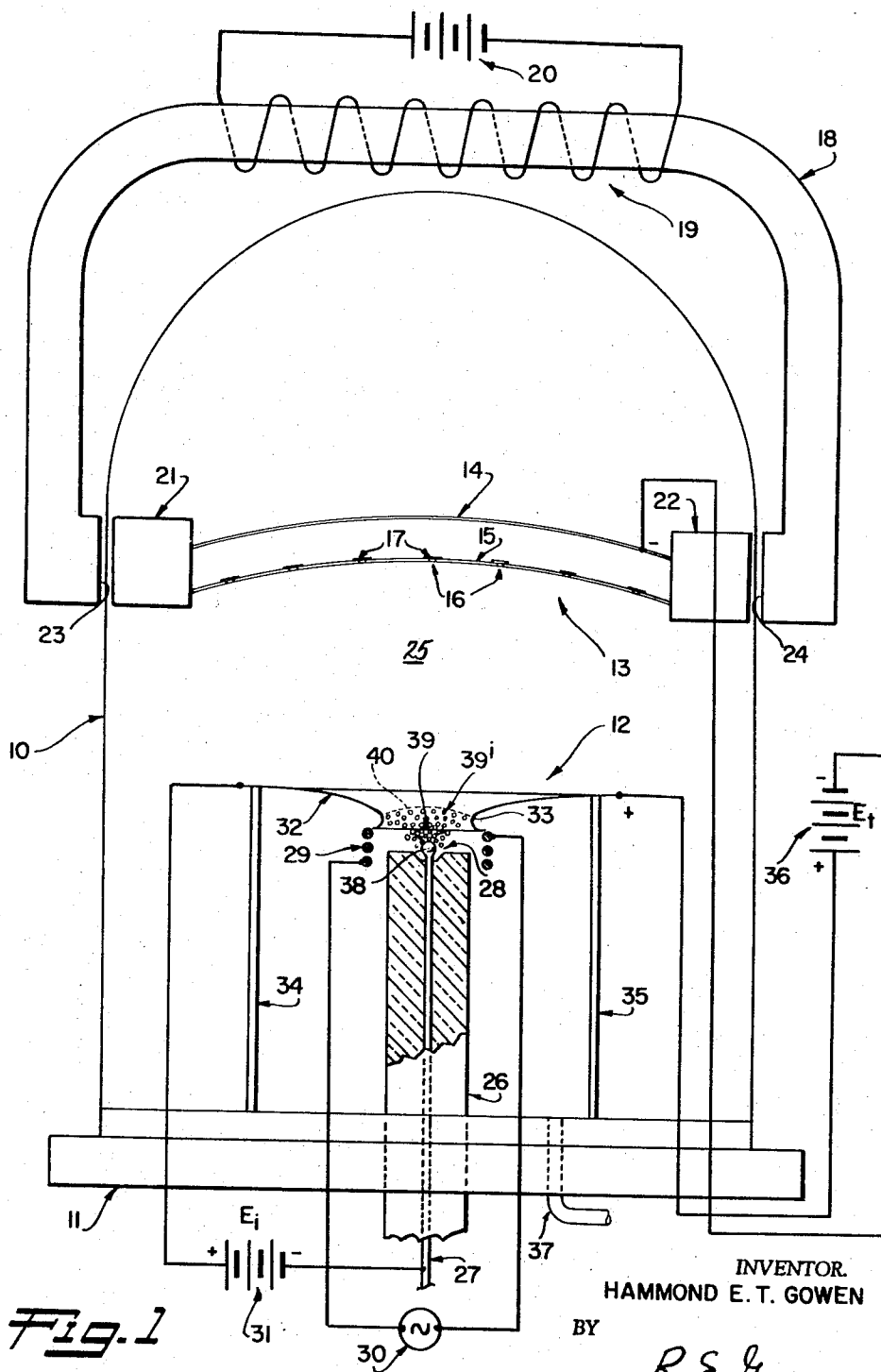


Fig. 1

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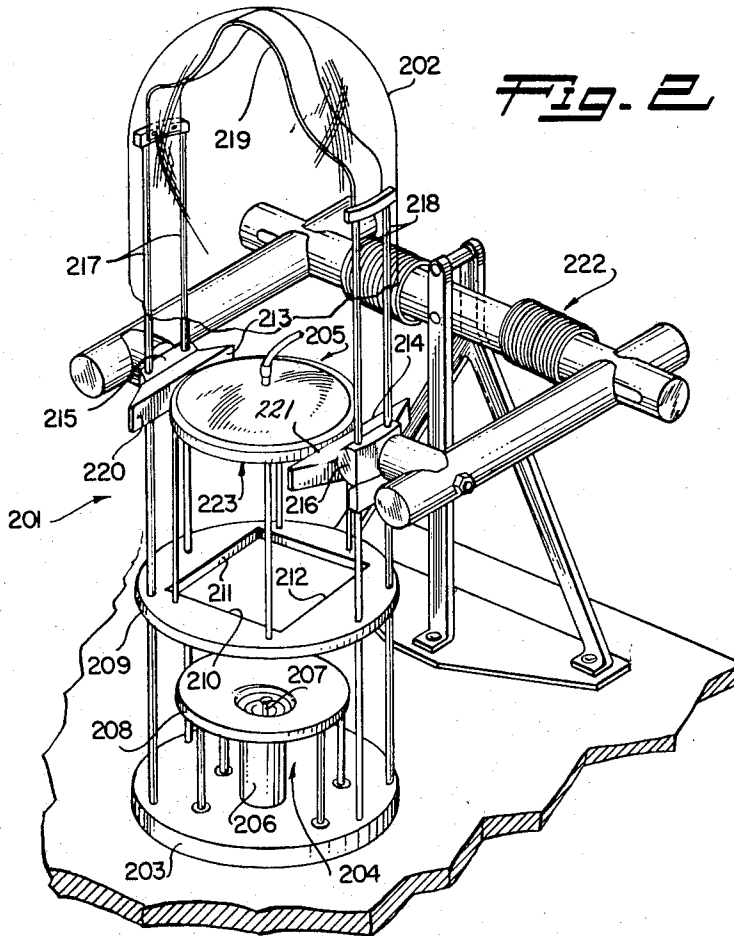


Fig. 2

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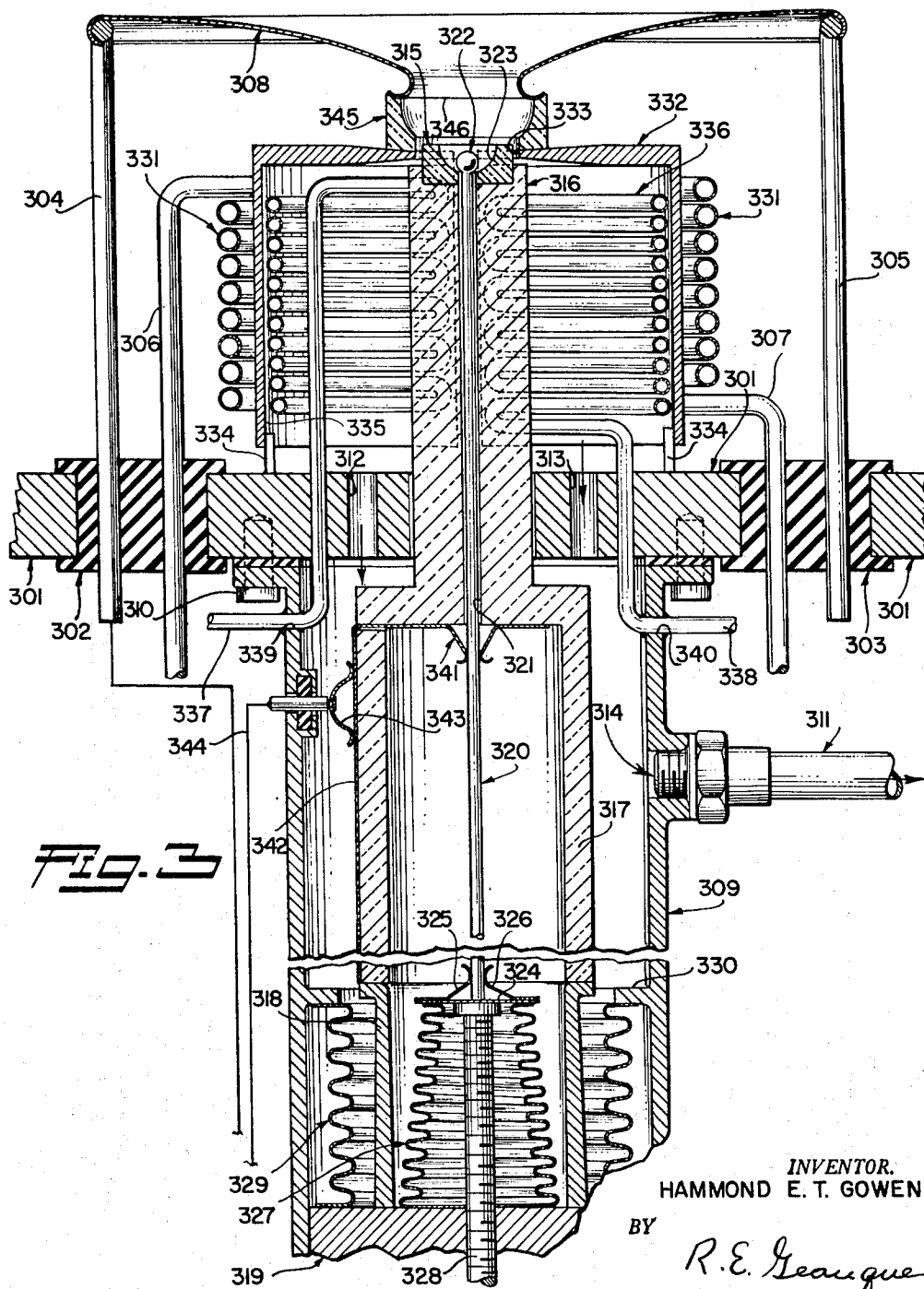
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7 Sheets-Sheet 4

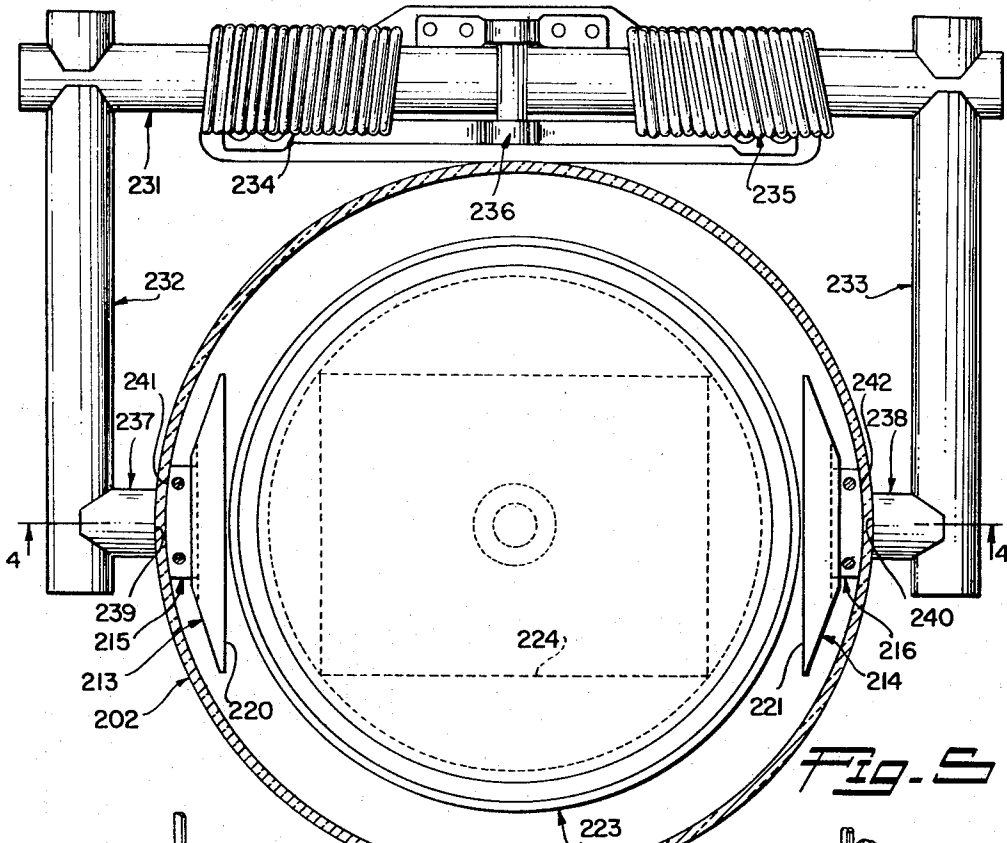


Fig. 5

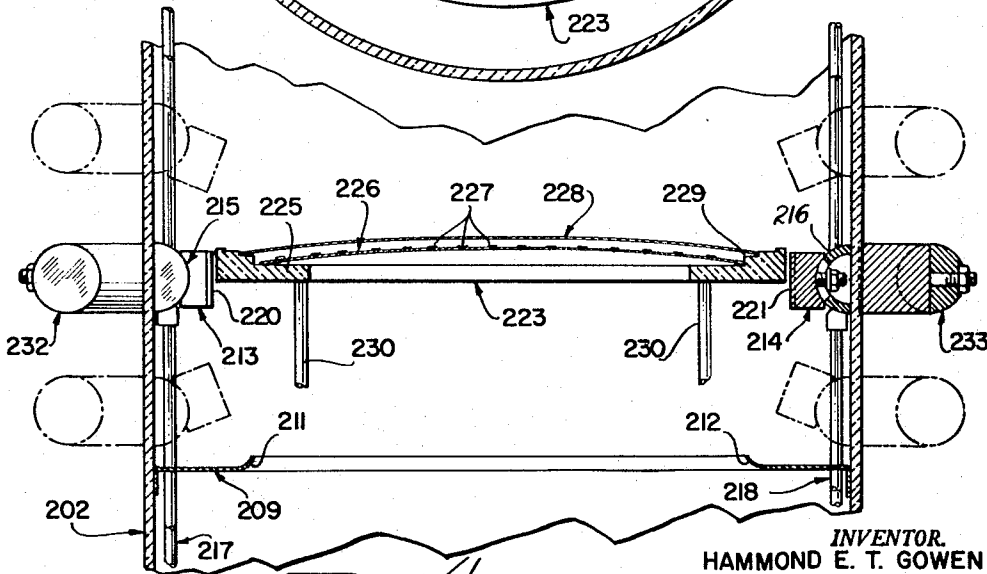


Fig. 4

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7 Sheets-Sheet 5

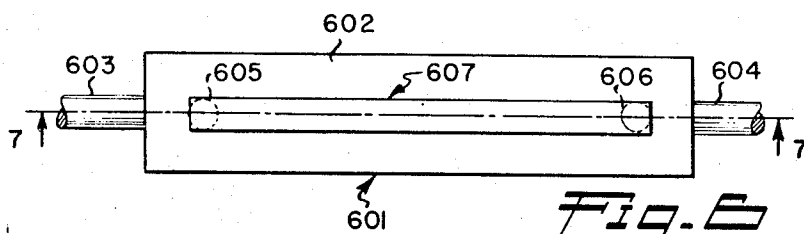


Fig. 6

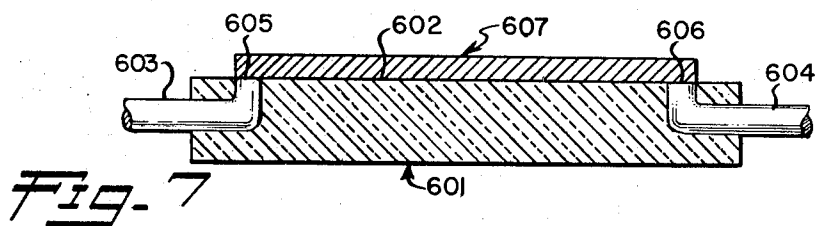


Fig. 7

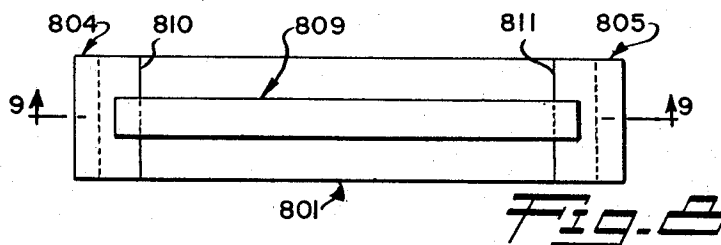


Fig. 8

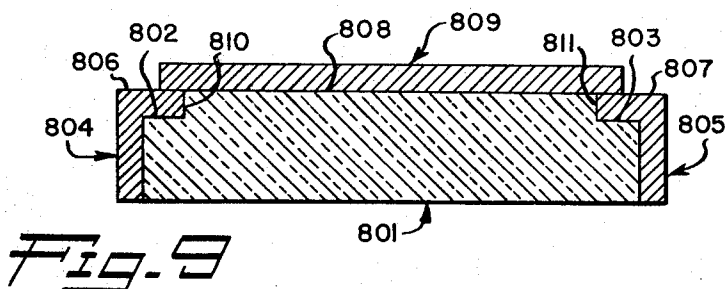


Fig. 9

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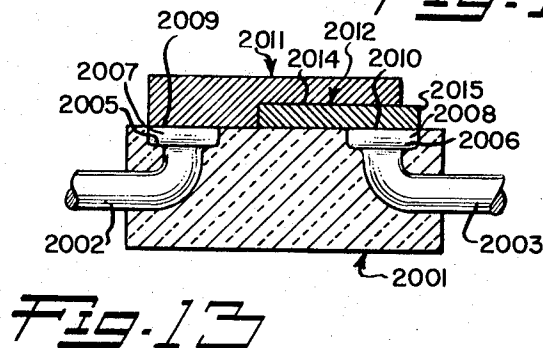
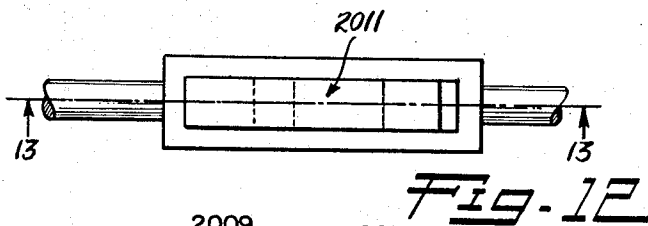
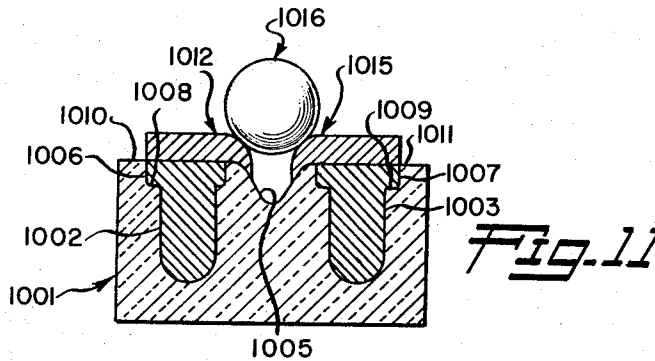
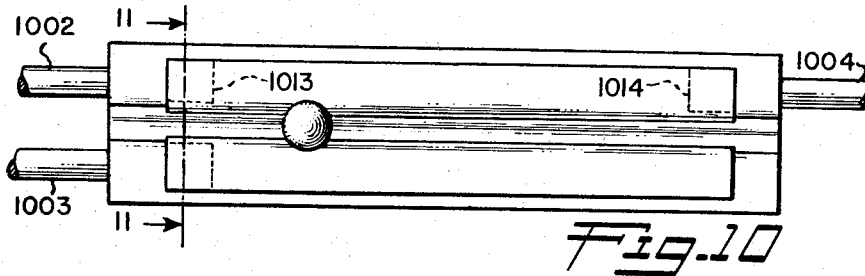
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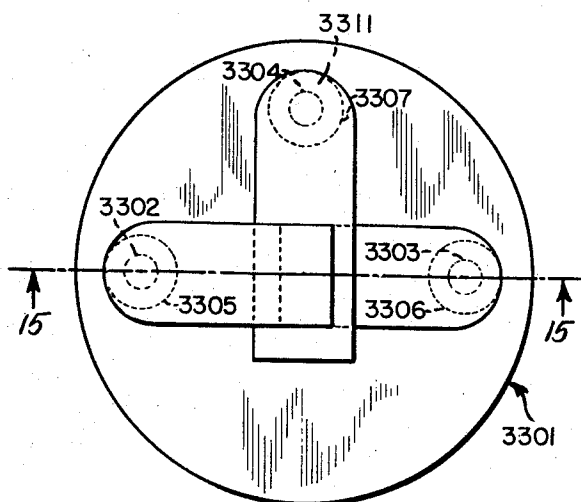


Fig. 14

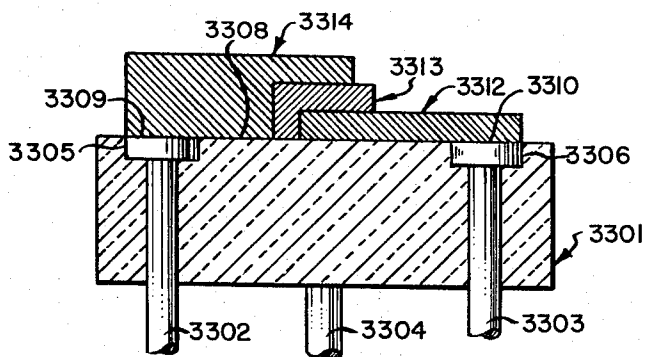


Fig. 15

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MEANS FOR CONTROLLED DEPOSITION AND GROWTH OF POLYCRYSTALLINE FILMS IN A VACUUM

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Application Nov. 16, 1965, Ser. No. 511,285, which is a continuation of application Ser. No. 58,144, Sept. 23, 1960, now Patent No. 3,290,567, dated Dec. 6, 1966. Divided and this application Sept. 9, 1966, Ser. No. 578,290

10 Claims. (Cl. 118—49.1)

This application is a division of application Ser. No. 511,285, filed Nov. 16, 1965, now Patent No. 3,290,567, which is in turn a continuation of application Ser. No. 58,144, filed Sept. 23, 1960, now abandoned, by Hammond E. T. Gowen, entitled, Controlled Deposition and Growth of Polycrystalline Films in a Vacuum.

The present invention relates to apparatus for vacuum deposition of thin crystalline films and more particularly, to apparatus for effecting controlled deposition and growth of polycrystalline films in a vacuum and more particularly to apparatus for depositing monocrystal-thick polycrystalline layers of metals, and/or non-metals upon either crystalline or noncrystalline substrates, and/or upon each other for building electrically conductive, semiconductive, and non-conductive structures as desired in accordance with the teachings herein. Such structures may include broadly known types of existing devices such as electrical resistance elements both of the fixed value types and potentiometer types, surface heating and heat radiating devices, semiconductor devices including diodes, transistors and radiation converters of known types as well as several new types, thermoelectric converters for heating and/or cooling, thermoelectron generators, and cathodes for stressed-field vacuum tubes

Additional structures can be built by variations in or combinations of the above-noted devices, such additional devices being broadly known as micro-modular circuits and molecular three-dimensional circuits.

In general, the apparatus of the invention involves the use of a high vacuum and comprises the three broadly designated means for generating ions of the material to be deposited, means for transporting such ions to the substrate for deposition thereon, and means for effecting crystallization of the material upon the substrate in accordance with the predetermined dimensions and nature of the crystal growth desired.

In the past, thin solid films have been prepared on metallic or non-metallic supports or substrates by several different techniques, the principal procedures for the deposition of metals being electro-deposition, chemical precipitation (notably of silver), thermal decomposition on a heated substrate of a metal halide or of a metal carbonyl gas, and explosion of metal wires in an inert gas. The principal techniques for the deposition of both metals and non-metals (dielectrics) have been chemical reaction of a metal halide and water vapor to form a metal oxide, cathodic sputtering of metals or metal oxides in a low pressure glow discharge, and vacuum evaporation of metals and thermally stable compounds. Growth processes are referred to as epitaxial when the material grown forms an extension of the crystal structure of the substrate.

Each of the foregoing coating methods imposes some limitations on the substrate material such as, for example, it must be capable of withstanding a high temperature, water immersion, or it must be crystalline. In the past, vacuum deposited films have been invariably granular in texture, but for layers of the order of 0.1 micron thick, grain growth is usually sufficiently small for the deposit

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to faithfully contour the substrate surface. Also, methods have been devised for epitaxially growing a single crystal upon a substrate. However, such techniques involve a replication of the unit cells of the crystal from a seed crystal. In contrast, the structure of the present invention for carrying out the new process does not rely upon a seed crystal and replication of additional cells thereupon. More particularly, the structure of the present invention and the mode of operation thereof results in the formation of a plurality of crystals from a liquidus supply of the material to be crystallized, but without the need of a seed crystal.

In the past, the practical upper limit in the thickness of an evaporated deposit has been of the order of a micron. Films of greater thickness have been usually extremely brittle.

Evaporation techniques in the past have relied almost entirely upon the interception by the substrate of vaporized particles moving in a random manner within the vacuum chamber. Hence, only those source materials have been practical utility that have relatively high vapor pressures so that sufficient energy for travel could be imparted to the particles by vaporization alone.

Films deposited on substrates by vacuum techniques in the past have encountered the counteracting effects of cohesion of the particles of the film to each other and adhesion of the film to the substrate. The structure of a condensed film is partially dependent on the extent of the interfacial forces at the film-substrate boundary. Thus, when the interfacial forces are less than the cohesive forces in the film, the preferred film structure will be agglomerated because of the greater attractive force between the condensed atoms as compared to the attractive forces of the substrate atoms to the condensed atoms. Conversely, when the interfacial forces are the greater, the deposited film will have greater adherence to the substrate. Hence, methods that have been used for attaining a high degree of film adherence to the substrate have also affected the structure and, in turn, the physical properties of the condensed layer. Forms deposited by use of the apparatus of the present invention employ both molecular and mechanical adhesion forces to secure the film to its substrate.

Thus, it is one of the principal objects of the present invention to provide apparatus for obtaining thin films on substrates, the atoms of such films having their maximum cohesive forces between themselves and adhesive forces with respect to the substrate. The inception of crystallization of the material comprising the film of the present invention commences from the liquidus state of the source material and is responsive to gravitational force, surface tension force, and an externally applied magnetic field to determine the size of the crystals thus formed in two gross dimensions, while permitting crystallization to proceed in the third gross dimension to any desired extent within certain practical limits. That is, the size of the individual crystals making up the polycrystalline layer, in two gross dimensions, are substantially fixed parameters as determined by the above gravitational and surface tension forces and the remaining gross dimension, considered herein as the thickness of the film is the variable parameter and may be selectively controlled.

The prior art science of crystallography has been directed and limited primarily to the creation of single gross crystals of a given material, whether such material is composed of a single element or a combination of elements, because of the methods known to the art for forming crystals. Since a single crystal grows in all directions, the crystals resulting from the prior methods of growth have had three gross dimensions and, consequently, have not been usable for obtaining a thin film which, in a practical sense, has only two gross dimen-

sions. Hence, in the making of semiconductor devices, the only practical method has been to grow a single crystal having three gross dimensions and then, by mechanically slicing or chemically etching, to create the thin crystalline portion desired. Several extreme disadvantages are present in such prior art methods. Obviously, any mechanical or chemical process which works upon a completed crystal for obtaining a small portion thereof is limited to dealing with a finite thickness of final product because of measuring and handling problems alone. Further, large crystals grown according to the methods of the semiconductor fabrication art are subject to stresses during growth due to temperature and rate-of-growth variations during the process, and also due to impurities present, so that amorphous and/or anomalous portions occur within the gross crystal structure. Thus, besides the breakage and loss of material problems, it cannot be predicted that each portion of the gross crystal will be identical to, or have the characteristics of, each other portion of such crystal. Part of the problem relates to the difficulty of obtaining even dispersion or distribution of the donor and acceptor impurities required for semiconductor materials. Although some efforts are being made in the art to produce a film of semiconductor material having only two gross dimensions, such efforts have been unsuccessful in several respects. For example, the films so produced have lacked mechanical strength due to both the inability of the film to form strong adhesion bonds to the substrate and cohesive bonds between atoms of the material. Further, the films have been subject to the presence of microscopic holes which introduce anomalous and unpredictable characteristics. Still further, such films are porous due to several factors, including the presence of a plurality of crystals stacked upon each other in the thickness dimension.

Therefore, it is a concomitant principal object of the present invention to provide apparatus for obtaining non-anomalous, non-amorphous, homogeneous, monocrystal-thick polycrystalline films of materials, including semiconductor materials of all types of conductivities. By "monocrystal-thick polycrystalline films" is meant a layer of crystals all of which are substantially the same size and which have contiguous monocrystal interfaces in two gross dimensions and in which the crystal faces in the remaining gross dimension are either in confrontation with a substrate or are openly exposed.

Therefore, it is another principal object of the present invention to provide apparatus for making semiconductor devices with controlled thicknesses and dimensions of each region in accordance with predicted characteristics, and to make P-N barrier regions of the minimum thickness obtainable consistent with crystal structures.

An additional problem, the severity of which is greater for some types of semiconductor devices as compared to others, relates to the surface leakage combination of current carriers (whether electrons or holes). Because of the present known methods of semiconductor fabrication, short surface paths are created between layers of semiconductor material of the same conductivity type across layers of the opposite conductivity type. In order to overcome or minimize this problem, devices have been etched or otherwise worked upon to provide longer paths. In many cases, such as the mesa transistor, this is not practicable. Even where possible to some extent, such additional working upon the crystal structure reduces the mechanical strength of the device as well as adversely affects the electrical characteristics.

Therefore, it is another object of the present invention to provide apparatus for obtaining semiconductor devices having long surface recombination paths.

One of the objects of the present invention is to provide apparatus for controlled deposition and growth of polycrystalline films in a vacuum.

Another object of the present invention is the provi-

sion of apparatus for generating a plasma of ions of a source material for controlled deposition of such material on a substrate in a vacuum.

Another object of the present invention is the provision of apparatus for obtaining controlled growth of a polycrystalline film on a substrate in a vacuum.

A further object of the present invention is the provision of apparatus for making semiconductor devices.

Another object of the present invention is the provision of apparatus for making resistance elements for fixed and variable resistance and potentiometer applications.

A further object of the present invention is the provision of apparatus for the production of monocrystal-thick polycrystalline films of homogeneous non-anomalous structure.

A further object of the present invention is the provision of apparatus for making semiconductor devices having improved performance characteristics such as frequencies of operation, current carrying and/or generating capabilities, and/or power levels.

According to the present invention, an apparatus is provided wherein neutralized atoms of a material on a substrate, in thin film form, are permitted to cook while in a vacuum and under the influence of a magnetostatic field, such field being oriented in a direction with respect to the surface of the substrate so that all of the atoms of material arrange themselves in accordance with a preferred orientation of crystal growth. For example, the preferred orientation may be with the 100, the 111, or the 110 axis of the crystal at a selected angle with respect to the plane of the substrate. The orientation of the atoms is achieved by the effect of alignment of the magnetomotive force of each atom with the lines of force of the magnetostatic field. In order for each atom to be free to move in accordance with such alignment tendency, the film of material must have sufficient thermal energy to maintain it in a liquid or, at least, liquidus state until crystallization begins. In certain prior deposition processes, the temperature of the substrate has been selectively controlled as a means for regulating crystallization. In contrast, the present invention maintains the temperature of the source material by imparting a selected amount of thermal energy to the material transported to the substrate rather than by separately controlling the temperature of the substrate. That is, in order to avoid polycrystalline buildup in layers, crystallization should take place throughout the entire body of the film at the same time. According to one aspect of the present invention, ionized atoms of the desired material are brought to the substrate surface from a remote source of such material and deposited upon the substrate in a manner that the energy requirements for maintaining the deposited material in a liquidus state are met. In order to assure uniformity of atomic energy levels, as well as uniformity of distribution and the proper rate of deposition of such atoms, an ion plasma is generated to constitute the remote source of film material and a potential gradient is imposed between such ion plasma and the substrate to cause the ions of source material to be transported to the substrate. Upon contact with the substrate, the ions are discharged of their ionic charge to form neutralized atoms. The transport potential gradient is chosen to have a value such that, empirically considering the distance of travel and the weight of the ions, the impacting ions will have sufficient kinetic energy to satisfy the energy requirements mentioned above. Thus, the velocity of an impinging ion is not so great as to cause such ion to either disrupt the crystalline structure or other nature of the impingement surface of the substrate by ion bombardment, nor to cause such ion to rebound from such impinged surface. On the other hand, the kinetic energy obtained by conversion of its kinetic energy is sufficient to maintain the already-deposited atoms in a liquidus state. Such energy relationships take into account the

factor of dissipation of thermal energy by the ion during its transportation, as well as other factors noted herein-after. Since the already-deposited atoms are losing thermal energy due to radiation and conduction effects, the rate of deposition of succeeding ions must be sufficient to replace such dissipated thermal energy. It should be noted that, if all of the atoms could be deposited in absolute simultaneity, there would be no requirement for replacement of thermal energy to "previously" deposited atoms and, hence, the kinetic energy of the impacting ions could actually equal only the thermal energy loss by such impinging ions during transport from the ion plasma to the substrate. To the extents that the films produced in accordance with the present invention are extremely thin, and the atoms could be deposited at an extremely fast rate, the factor of thermal energy replacement for already-deposited atoms is of a substantially lower order of magnitude than the factor of replacement of thermal energy lost during transportation of ions and, thus, can be relatively ignored. It has been determined empirically that, for metallic material, the direct current potential E_t used for generating the electrostatic transportation field between the ion plasma and the substrate should be approximately $1.2(A)(D)$, where (A) is the average atomic weight, by percentage, of the elements of the source material, and (D) is the distance, in millimeters, from the ion plasma to the substrate, in order to obtain the proper balance of all of the factors involved in the deposition of the ions upon the substrate.

The method for creation of the crystalline film is practiced in a vacuum chamber for several reasons, many of which are obvious to those skilled in the art. For example, ion plasma generation is extremely facilitated by the absence of vapor pressures due to foreign particles, whether air or otherwise. Also, a hard vacuum minimizes the possibility of collision between transported ions and stray atoms or particles. Also, since the energy of the impinging ions depends partially on the amount of thermal energy lost during transport, the elimination of stray particles minimizes the amount of heat lost through proximity of such particles during transport.

In generating a plasma of ions, a source material, which may be in the form of a wire, is fed into a heating region. The heat for such region may be obtained by radio frequency (R-F) energy supplied on an R-F coil wrapped around the heating region and having a configuration for concentrating the heat applied to the end of the source material wire. Sufficient heat should be supplied to vaporize the end of the wire. In the nature of things, the heat supplied to the end of the wire will cause a spherical ball of boiling material to be formed. As boiling continues, atoms of the material are vaporized and liberated from the boiling ball. An ionization field may be formed between the ball of material and the outer confines of the plasma region, as by means of a direct current potential for generating an electrostatic field. The ionization potential should be slightly in excess of the highest first ionization potential of any of the atomic elements contained in the source material desired to be transported to the substrate. Thus, if the source material is an alloy containing, for example, manganese and nickel, the ionization potential should be approximately 8 volts, nickel having a first ionization potential of 7.633 ev. and manganese having a first ionization potential of 7.432 ev., the first ionization potential usually being defined as the energy which is just sufficient for the complete removal of the most loosely bound electron, leaving a positively charged ion.

The features of the present invention which are believed to be novel are set forth with particularity in the appended claims. The present invention, both as to its organization and manners of operation, together with further objects and advantages thereof, may best be understood more fully by reference to the following additional description,

taken in connection with the accompanying drawings, in which:

FIGURE 1 is a diagrammatic illustration of one embodiment of the apparatus for practicing the method of the present invention;

FIGURE 2 is a perspective view, partly fragmentary, of one embodiment of apparatus in accordance with the present invention;

FIGURE 3 is an enlarged vertically sectioned view, partly in elevation, of the ion plasma generator portion of the apparatus illustrated in FIGURE 2;

FIGURE 4 is an enlarged vertically sectioned view, partly in elevation, of the crystallizer portion of the apparatus illustrated in FIGURE 2;

FIGURE 5 is an enlarged top plan view of the magnetostatic field generating a portion of the apparatus illustrated in FIGURE 2, partly in horizontal section through the crystallizer portion of such apparatus illustrated in FIGURE 4;

FIGURE 6 is a top plan view of one embodiment of a resistor made in accordance with the use of the apparatus of the present invention, and FIGURE 7 is a vertically sectioned view thereof, partly in elevation, as seen along line 7—7 in FIGURE 6;

FIGURE 8 is a top plan view of another embodiment of a resistor made in accordance with the use of the apparatus of the present invention, and FIGURE 9 is a vertically sectioned view thereof as seen along line 9—9 in FIGURE 8.

Similarly, FIGURE 10 is a top plan view of a resistance portion of a potentiometer, and FIGURE 11 is an enlarged vertically sectioned view thereof as seen along line 11—11 in FIGURE 10.

Similarly, FIGURE 12 is a top plan view of one embodiment of a semiconductor diode, and FIGURE 13 is a vertically sectioned view thereof, partly in elevation, as seen along line 13—13 in FIGURE 12.

Similarly, FIGURE 14 is a top plan view of a semiconductor triode transistor, and FIGURE 15 is a vertically sectioned view thereof, partly in elevation, as seen along line 15—15 in FIG. 14.

Referring to FIGURE 1, it should be understood that the apparatus is illustrated in diagrammatic form and that the relative dimensions and configurations have been exaggerated in some instances for the sake of clarity of illustration. A vacuum chamber 10 is seen to comprise a bell jar appropriately sealed to a base member 11. An ionizer, indicated generally at 12, is supported by the base member 11 and is located at the bottom of the vacuum chamber 10. A crystallizer, indicated generally at 13, is located near the top of the vacuum chamber 10 and includes (in its physical region) an electrostatically charged screen 14, a substrate support member 15 having a plurality of apertures such as 16 therethrough and shown to be provided with a plurality of substrates 17 disposed on the back thereof in generally receiving relationship in back of the apertures 16, a magnetostatic field source comprising a yoke electromagnet 18 with its field winding 19 and direct current power source 20 all located exteriorly of the vacuum chamber 10, and internal field poles 21 and 22 located inside of the vacuum chamber 10 and in alignment with the respective pole faces 23 and 24 of the external yoke electromagnet 18. The area between the ionizer 12 and the crystallizer 13 is indicated generally at 25 and may be called a plasmionic field or area for the purposes of this invention. The ionizer 12, which may also be called a plasmionic generator, includes a ceramic member 26 which acts as a support and guide for a wire 27 composed of the source material to be deposited. The end 28 of the wire 27 projects out of the support member 26 and is surrounded by heater coils 29 which are connected to a power source 30 of radio frequency energy. A low direct current potential source 31 has its negative side connected to the source material 27 and its positive side connected to an ionizing ring 32. The ionizing ring 32

has a central opening 33 of circular configuration and disposed in central alignment above the end 28 of the wire 27. The ring 32 is supported by rods 34 and 35 which may be composed of ceramic material or other non-conductive substances. A D-C voltage gradient is established across the plasmionic field area 25 between the ionizer 12 and the crystallizer 13 by means of a high potential direct current source 36 having its positive side connected to the ionizer ring 32 and its negative side connected to the charging screen 14. A conveniently located conduit 37 is disposed through the base member 11 for communication with the interior of the vacuum chamber 10 and is connected to a vacuum pump (not shown) for evacuation of the chamber 10.

The operation of the apparatus generally illustrated in FIGURE 1 may be described as follows. First, the vacuum chamber 10 is evacuated to an extremely low pressure which is referred to as a high vacuum, such pressure being in the order of 10^{-6} inches of mercury or even lower. The main objects of such a high vacuum are to minimize the collisions of the film ions with the ambient gas particles as the ions traverse the plasmionic field 25, to minimize the contaminants in the film deposit, and to prevent any corona discharge due to the presence of any foreign gas particles within the high potential fields utilized. Collisions of film ions with foreign particles in the plasmionic field 25 would cause the undesired effects of loss of the kinetic energy of the ions so that they may not reach the substrates 17, neutralization of the desired ions so that they will no longer be affected by the otherwise attractive force of the negative charging screen 14, and, even if such collided ions do reach the substrates 17, they will be contaminated with the particles with which they collided. Upon attaining the desired vacuum within the chamber 10, the wire or rod 27 of the source material is pushed up through the ceramic support 26 until approximately one-eighth inch of its end 28 is exposed. Then the R-F generator 30 is energized to create intense local heat on the end 28 of the wire 27 for vaporization thereof. As the temperature of the wire end 28 is raised by the heating field from coils 29, it will melt and form a ball 38 of molten source material. Continued heating of the wire end 28 and the ball 38 of molten source material causes atoms, indicated generally at 39, to be liberated from the molten ball 38. At this time, such atoms 39 do not have any particular charge nor orientation nor preferred direction of travel but simply disperse according to random distribution. Of course, such random distribution is somewhat affected by the continuous release of additional atoms from the molten ball 38 with the concomitant vapor pressure thereby causing the atoms 39 to congregate somewhat outwardly from the ball 38. An electrostatic field having a potential gradient in accordance with the ionization potential E_i is established between the ionizer ring 32 and the molten ball 38, the ionizer ring 32 being positive with respect to the ball 38. This electrostatic field will establish a virtual mirror, indicated by the dash line 40, beyond which the atoms 39 will not pass except under conditions to be described hereinafter. The ionization potential E_i is sufficient to cause the atoms 39 to be ionized, i.e., the ionizer ring 32 will pull an electron from each of the atoms 39 affected by the ionization field. For convenience of description, those atoms 39 which have become ions will be referred to by the designation 39^+ . Each of the ions 39^+ will have a positive charge because of the absence of the electron. Having a positive charge, each of the ions 39^+ will be repelled by the ionizer ring 32 and its virtual mirror 40 toward the negatively charged molten ball 38. Of course, due to the continuous process of withdrawal of electrons by the ionizer ring 32 from the cloud of atoms 39, a cloud of ions 39^+ will be created. In the absence of any external forces, the cloud of ions 39^+ will be constrained to the field area generated by the ionizing field between the ionizer ring 32 and molten ball 38. Of course, some ions may escape due to the internal field pressures of such a cloud of ions

against the constraining field. Because of this characteristic, the cloud of ions 39^+ will be referred to as a plasmionic cloud. The ions 39^+ , each having a positive charge, will tend to repel each other and remain as distinct ion particles. While there will be some interchanging of electrons between ions 39^+ and atoms 39 immediately adjacent the molten ball 38, those ions 39^+ adjacent the virtual mirror 40 will remain in their ionized conditions. Now, upon energization of the high potential direct current source 36 having a potential E_t , an electrostatic field potential gradient will be established across the plasmionic field 25 from the ionizer ring 32 to the charging screen 14, such field including the area occupied by the mask 15 and the substrate articles 17 disposed therebehind. As is indicated, the charging screen 14 is connected to the negative side of the E_t potential source 36, and the ionizer ring 32 is connected to the positive side of the source 36. The virtual mirror 40 constitutes a spherical equipotential plane from either side of which the potential gradient becomes more negative; therefore, the virtual mirror 40 is effectively a zero potential plane with respect to the field on either side thereof. Therefore, those ions 39^+ which have not passed beyond the virtual mirror 40 will not be affected by the potential gradient in the plasmionic field 25. However, those ions 39^+ which have passed beyond the virtual mirror 40 due to the pressures of the constantly increasing numbers of ions 39^+ in the plasmionic cloud within the ionizing field, will be rapidly transported across the plasmionic field area 25 toward the charging screen 14 because of the attractive force of the negatively charged screen 14 upon the positively charged ions 39^+ , such "attractive force" merely being another way of expressing the effect of the electrostatic field potential gradient established by the potential E_t across the plasmionic field 25. In the absence of any forces in the plasmionic field 25 other than those due to the transport potential E_t , each of the ions 39^+ will travel in a straight line path towards the charging screen 14. Of course, none of the ions 39 can ever reach the charging screen 14 because of the physical barrier imposed by the location of the mask 15 with the substrates 17 between the ionizers 12 and the charging screen 14. However, according to the present invention, a magnetic field is located across the entire area of the crystallizer 13 by means of the electromagnet 18 and its associated components. With various exceptions, which will be described with more particularity later, the magnetic field across the crystallizer 13 establishes lines of flux substantially parallel to the mask 15 and the surfaces of the substrates 17. The flux density of the magnetic field in the region of the substrates 17 will be determined by the desired properties of the film produced, but typically may be of the order of a fraction of a gauss to a few gauss between field poles 21 and 22. A more detailed description of the magnetic field and the apparatus for its generation will be given in connection with FIGURES 2 and 3. Let it suffice for the moment to regard the magnetic field lines of flux as parallel to the surface of each of the substrates 17 upon which a film or films will be deposited. The magnetic field causes the ions 39^+ to spin slightly in a somewhat spiral trajectory about their otherwise straight-line path of travel from the ionizer 12 toward their eventual points of impact. This combination of magnetostatic and electrostatic stresses promotes a very even distribution of the ions as they approach the substrates 17 (as well as the mask 15). Upon reaching the substrates 17, each of the transported ions 39^+ will gain an electron and, thus, become discharged or neutralized so as to return to its full atomic valence state. Thus, the ions 39^+ will have returned to their condition as previously designated by the numeral 39 and will have been merely transported from the atomic cloud at the molten ball 38 to contact with the surface of the substrates 17. For convenience of designation in description, the neutral atoms deposited upon the substrates 17 will be designated as 39^0 . At the moment of impact with the substrates 17, the ions 39^+ and the immedi-

ately discharged atoms 39^a will still have their heat of vaporization. This heat can be lost only by direct radiation. It should be noted and understood that the magnitude of the transport potential E_t should not approach a value sufficient to cause the impinging ions 39^i to bounce from or otherwise leave the surface of the substrates 17 upon impact. However, the transport potential E_t should have sufficient magnitude to remove those ions 39^i from just beyond the virtual mirror 40 as rapidly as they pass such mirror 40 due to both the random effects and the vapor pressure of the continuously released and ionized atoms within the plasmionic cloud. Of course, the optimum formation of the plasmionic cloud by the ionizer 12 is a converse function of the optimum transport potential E_t desired to be utilized for the purposes of the present invention. Returning now to the neutralized atoms 39^a , these atoms will immediately begin to form a eutectic film on the surface of the substrates 17. This eutectic film is kept in a state between liquidus and solidus by the reaction energy of impact of the subsequent impingement upon the substrates 17 and the previously arrived neutral atoms 39^a of the ions 39^i . Of course, as each newly arrived ion 39^i contacts the substrate 17 or the previously deposited neutral atoms 39^a , such ion 39^i will be similarly discharged or neutralized. Upon being neutralized, the neutral atoms 39^a upon the surface of the substrate 17 will no longer be affected by the electrostatic field of the transport potential E_t . If left to themselves, the neutral atoms 39^a will have a random orientation and distribution with respect to each other with the exception of the effect of wetting action which naturally occurs between atoms or particles in the liquid or even eutectic state. However, the parallel lines of flux due to the magnetic field established by the electromagnet 18 alter this random orientation and distribution in a manner in accordance with the present invention. Such effects may be described in the following manner:

Firstly, although not necessarily of the primary importance, the lines of flux will constrain the neutral atoms to a planar film distribution upon the substrate surface. That is, any random tendency of the neutral atoms 39^a to pile upon each other or otherwise seek a level represented by a configuration other than a uniform film thickness will be eliminated. Secondly, in accordance with their nuclear magnetic moments, each of the neutral atoms 39^a will tend to become aligned in a direction related to the unidirectional flux lines of the magnetic field. Thus, each of the neutral atoms achieves a stress-relieved orientation with respect to each of the other neutral atoms 39^a . Such orientation permits subsequent crystal growth in accordance with the well-known orderly and preferred disposition of atoms within a crystal.

The virtual mirror 40 created at the ionizer ring 32 does not occur until both the ionization potential E_i and the transport potential E_t have been applied. In the absence of the transport potential E_t between the ionizer ring 32 and the charging screen 14, the plasma-ionic cloud will be constrained to the area between the ionizer ring 32 and the molten ball 38 simply by virtue of the potential gradient in that region established by the ionization potential E_i . Therefore, some of the ions will actually be above the physical continuation of the ionizer ring 32 across its opening 33. Upon application of the transport potential E_t , the interaction of the two electrostatic fields of the ionization potential E_i and the transport potential E_t will cause the creation of a virtual mirror 40 between the two fields. This virtual mirror 40 will be a spherical plane of zero potential. By zero potential is meant the reference potential of the ionizer ring 32. The virtual mirror 40 will be a spherical plane because of the configuration of the "electrodes." That is, the molten ball 38 is an effective electrode of a spherical configuration and the charging screen 14 is also of a spherical configuration. Thus, the interacting field will have spherical planes of equipotential. The virtual mirror 40 is the zero equipotential spherical plane

and is located at the ionizer ring 32 because such ring is the central electrode between the two opposing electrostatic electrodes, i.e., the molten ball 38 and the charging screen 14. Thus, the virtual mirror 40 acts as he effective ion source for transport of the ions 39^i from the plasmionic generator 12 to the crystallizer 13. As fast as the ions 39^i are pulled from the virtual mirror 40 toward the charging screen 14, additional ions will replace such departed ions.

The transport potential E_t is chosen at a value which takes into consideration the following factors. The ions 39^i should not be permitted to gain so much kinetic energy, due to acceleration during transport, that they bounce or splatter from the substrate upon impingement. However, it is desired that the thermal energy of the ion remains the same upon deposition as upon leaving the virtual mirror 40. Therefore, the transport potential is chosen so that the kinetic energy imparted to the ion is approximately the same as the thermal energy lost by the ion during transport. Therefore, the conversion of the kinetic energy to thermal energy upon impact will leave the ion with substantially the same amount of thermal energy as it had upon leaving the virtual mirror. Transport time may be approximately one meter per second. Since the ion may be travelling approximately one-third of a meter in the vacuum chamber, the amount of time for transport may be approximately one-third of a second. Insofar as the relative values of ion transportation rate and ion generation rate are concerned, ions 39^i will be generated at a much greater order of magnitude than they will be transported so that there is no problem of insufficiency of ions 39^i at the virtual mirror 40 in terms of availability for transportation to the crystallizer 13.

One of the effects of the R-F field is to cause a tornado or orbiting effect of the ions 39^i and atoms 39^a about the molten ball 38 within the ionization field region. Such vortex effect upon the ions and atoms within the region below the virtual mirror by the R-F field is not considered to be either harmful or helpful in terms of the overall method. In the event any ions have a spin imparted to them by the vortex which is still in effect at the time they leave the virtual mirror 40, such effect will be at least of a fourth order of magnitude and will virtually disappear prior to reaching the magnetic field region of the crystallizer 13 whereupon a spin is again caused to be imparted to such ions 39^i by the magnetic field.

The vapor pressures in the ionization field region will vary somewhat between the molten ball 38 and the virtual mirror 40. For example, the vapor pressure at the virtual mirror 40 may be in the order of 2×10^{-5} mm. of Hg whereas the vapor pressure immediately adjacent the molten ball 38 may be in the order of 5 or 6×10^{-5} mm. of Hg. The rate of vaporization of atoms 39 from the molten ball 38 is affected by the relative vapor pressures due to thermal agitation within the molten ball 38 and the external vapor pressure immediately adjacent the molten ball 38. The external vapor pressure is due to the tendency of the ions 39^i to return to the ball since the ions 39^i are positively charged and the ball 38 has a negative polarity. The vortex created by the R-F field will have little or no effect upon such relative pressures. The ion and atom density between the molten ball and the virtual mirror is not linear but is affected by innumerable factors including the configuration of the ionizer ring opening, the spacing between the ionizer ring and the molten ball, the atomic weight of the materials involved, the rate of vaporization from the ball, the rate of pull-off from the virtual mirror by the transport potential, the vortex created by the R-F field, variations in the earth's magnetic field, and so forth, all of which factors are relatively immaterial since, as far as the method of the present invention is concerned, it is only necessary that ions 39^i be available at the virtual

mirror 40 as a source of ions for transport to the crystallizer 13. It is relatively unimportant what occurs between the virtual mirror 40 and the molten ball 38 as long as sufficient quantities of ions are generated. Such ion generation capability may be at least three or four times the rate at which ions 39ⁱ are pulled from the virtual mirror 40. In other words, atoms 39 may leave the molten ball 38 at a rate of three or four times the rate at which ions 39ⁱ are leaving the virtual mirror 40. Of course, the term "ion generation" may be used in the sense of release from the virtual mirror 40 in terms of overall effect, although ions may be generated within the plasma field and then returned to the molten ball at a rate of three or four times the ion dispersion from the virtual mirror. Thus, the "net" ion generation is a measure of the quantity or rate of ions transported from the virtual mirror. The rate of equilibrium is the rate at which ions leave the virtual mirror. Preferably, the rate of ion generation within the ionization field region should be at least three or four times the equilibrium rate in order to assure the fact that the ions 39ⁱ at the virtual mirror 40 will all be of the desired type and will not include impurities or negatively charged particles.

The order of cutoffs of each of the various potentials and fields involved is as follows: First, the transport potential E_t is cut off, then the R-F heating potential, then the magnetic field, and then, last, the ionization potential E_i . Upon initial cutoff of the transport potential E_t , the virtual mirror 40 will disappear and the ionization potential field will be effectively re-expanded upwardly into the transport region so as to recapture a large quantity of the ions 39ⁱ in transport. Such ions, no longer having the transport potential gradient to accelerate them toward the crystallizer 13, will be drawn back toward the ionizer ring 32 and the molten ball 38 which is, generally, the negative electrode. Those ions which have approached very closely to the substrate will continue in their path of travel toward the substrate for impingement thereon, with the exception of those ions which are randomly dispersed due to the spiraling effect of the magnetic field. Upon the occurrence of crystallization upon the substrates, the magnetic field is cut off. Crystallization may occur within a matter of a fraction of a second but, at least, the magnetic field will be cut off within ten seconds after cutoff of the transport potential E_t . The ionization potential E_i is cut off last for several reasons, including the fact that it will have no effect upon the crystallization at the crystallizer so that there is no reason for cutting it off earlier on behalf of crystallization, and also because the extension of the ionization field into the transport region 25 will aid in withdrawing ions 39ⁱ from the transport region 25 back toward the ionization ring 32 and the cup in ceramic 26. Of course, there will be some random ions and atoms subsequent to the various cutoff periods which will become deposited upon the walls of the vacuum chamber 10 and other structural elements within the vacuum chamber 10. Such deposits will be extremely low in density and will not tend to form crystalline layers but will be somewhat in the form of dust that can be easily wiped out. However, those ions which reach the cup and the source material wire 27 may form amorphous crystals because of the heat of the cup and wire 27. Such crystals might be difficult to wipe out but that is of little concern since, upon re-energization of the entire apparatus for the next shot, the majority of the so-deposited crystals will again form part of the plasmionic cloud.

There are numerous factors which have to be taken into consideration not only in the physical configuration of the elements within the vacuum chamber but also in terms of the relative spacing and the values and magnitude of the potentials in fields applied. Some of the more important of these factors are as follows:

(1) The ionization potential should be kept at a value between the first and second ionization levels so as not to

reach or exceed the second level of ionization of the material being ionized. Therefore, for most materials being utilized in this process, the ionization potential should not exceed ten volts;

(2) The shape of the ionization field is controlled primarily by the shape of the ionizer;

(3) The location of the ionizer ring is relatively critical in relation to the formation of the virtual mirror. The virtual mirror has to be created in free space which means it should be far enough away from the ionizer that it is not distorted by the thermal energy from the R-F source around the cup and the source material wire;

(4) There should be room for formation of a plasmionic cloud, including allowance for the vortex generated by the R-F field;

(5) The virtual mirror should have a radial center common to the radial center of the charging screen. Therefore, the equipotential plane of the virtual mirror should not be either too high or too low in its terminal intersections with the ionizer ring because of the changes in radial center of the equipotential plane as it is moved upwardly or downwardly with respect to the ionizer ring;

(6) The acceleration or transportation potential should be correlated to the distance traveled or to be traveled by the ions. That is, the transportation potential should not be excessive or else the ions will be re-bound from the substrate upon impingement. Also, the transportation potential must not be too low or else several adverse effects occur such as, for example, insufficient kinetic energy will be imparted to the traveling ions to replace the thermal energy lost during transportation, the relative effects of the electrostatic transport field with respect to the magnetic field will be decreased so that the relative spin motion of the ions will be increased compared to the radial path of travel of the ions (that is, the ions will take longer to traverse the distance to the substrates because they will be traveling a longer path occasioned by the magnetic field spin so that the ions lose more of their thermal energy, and so forth);

(7) The thermal transfer in flight should balance the energy picked up in terms of kinetic energy so that the conversion of kinetic energy back to thermal energy upon impact will almost exactly replace the thermal energy lost due to transfer in flight;

(8) The control and shape of the magnetic stress field in the crystallizer should be considered because the controlled growth of the crystal is caused by magnetic moment orientation of each of the neutralized atoms upon the substrate. If the magnetic field is too strong, the crystal may be distorted because too strong a field tends to cause precessing of the atoms;

(9) There should be the proper space in the ion generator for control of the R-F heating coil so as to minimize interaction between the vortex created by the R-F field and the electrostatic field in the transport region; and

(10) The ionizer ring should act as a static shield to give a proper separation between the ionizer and the transport field.

All of the above are only the major factors that should be taken into account in determining the configuration and spacing of the various elements. There are various relatively minor problems, mostly of a mechanical nature, such as shielding of some of the components against electrostatic fields and against formation of metal films from the source material which would establish leakage paths for the acceleration potential, mechanical configuration for assuring smooth contact between the inner and outer pole pieces on both sides of the walls of the vacuum chamber, springs or other means for preventing bouncing or other physical hardships against the glass wall chamber, and internal mounting structure for various elements.

Referring to FIGURES 2, 4, and 5, there is seen a preferred embodiment of apparatus in accordance with the present invention for depositing a monocrystal-thick polycrystalline film on a substrate or a plurality of sub-

strates. A vacuum chamber, indicated generally at 201, includes a glass dome 202 positioned upon and adapted to be sealed to a base member 203. Positioned within the vacuum chamber 201 are an ionizer, indicated generally at 204, and a portion of a crystallizer, indicated generally at 205. A more detailed description of the ionizer 204 will be given in connection with FIGURE 3 which shows one form thereof. For the moment, it should suffice to point out the ceramic cup 206 through which the source material is fed in the form of a wire 207 centrally located with respect to the ionizer ring 208. A shield 209 is located between the ionizer 204 and the crystallizer portion 205 and is provided with a square opening 210 whose parallel sides 211 and 212 are also parallel to the inner pole pieces 213 and 214 of the crystallizer 205. The crystallizer portion 205 within the vacuum chamber 201 includes the inner pole pieces 213 and 214 and their respective orientation members 215 and 216, the latter being mounted upon the parallel guide members 217 and 218, respectively. The guide members 217 and 218 are connected to opposite ends of a spring 219 which is adapted to contact the top of the glass dome chamber 202 for purposes to be described later. The inner pole pieces 213 and 214 are provided with respective planar surfaces 220 and 221, and the mechanical construction of the orientation members 215 and 216 as well as the external yoke, indicated generally at 222, is for the purpose of maintaining the planar surfaces 220 and 221 in parallel spacial opposition to each other at all times. However, it should be noted that, where special applications may require distortion of the magnetostatic field between the pole pieces 213 and 214, the planar surfaces 220 and 221 thereof may be oriented in any relationship to each other that is desired for obtaining such distorted field.

Located within the crystallizer region, see FIGS. 4 and 5, is a ceramic support member 223 of a substantially circular peripheral configuration and having a square central opening 224 spacially oriented in the same manner as the square opening 210 of the shield 209. The ceramic support member 223 is provided with an internal inner shoulder 225 upon which rests a substrate support 226. Substrates 227 are located on the upper surface of the substrate support 226. A charging screen 228 rests upon another shoulder 229 of the ceramic support member 223. Support member 223 is held in place by rods 230.

The yoke magnet, preferably composed of soft iron having an absolute minimum of remanence, includes three circular bars 231, 232 and 233 arranged in a U-shaped configuration. Balanced coils 234 and 235 are connected in series-aiding relationship to each other to a source (not shown) of direct current potential. The central bar 231 is pivotally mounted at its center to a frame, indicated generally at 236. The parallel magnet bars 232 and 233 are provided with adjustable external pole pieces 237 and 238, respectively, having respective faces 239 and 240 curved to fit the curvature of the glass dome 202. The orientation members 215 and 216 have respective outer faces 241 and 242 similarly curved to fit the curvature of the glass dome 202. As noted by the dotted line positions of the magnet assembly in FIGURE 4, the inner pole pieces 220 and 221 are pivotally mounted upon the respective orientation members 215 and 216.

Referring to FIGURE 3, there is seen a vertically sectioned view, partly in elevation, of one form of ion plasma generator for use in the apparatus illustrated in FIGURE 2. The base member 301 is provided with two electrical pass-through insulators 302 and 303 through which the ionization potential terminals 304 and 305 and radio frequency terminals 306 and 307 are passed in vacuum sealed relationship. Ionization potential terminals 304 and 305 are connected together externally to the source (not shown) of ionization potential, both of such terminals having the same potential applied thereto. An ionizer ring 308 is electrically connected to, and mechanically supported by, the ionization potential terminals 304

and 305. A cylindrical chamber 309 is secured to the base member 301 by bolts 310 and contains the source material feeder assembly to be described. A vacuum line 311 is connected to a vacuum pump system (not shown) and communicates with the interior of the cylindrical chamber 309 and, through the ports 312 and 313, with the interior of the vacuum chamber disposed above the base member 301, the evacuation flow being in accordance with the arrows indicated through the ports 312 and 313 as well as the arrow 314 into the vacuum line 311. A ceramic cup member 315 rests upon a rectilinearly vertically movable ceramic column 316 which has an open-ended cylindrical bottom portion 317 which, in turn, rests upon a cylindrical extension 318 of a cup-driving piston 319. The piston 319 may be driven by any convenient source of power for moving the cup 315 and its supporting assembly upwardly or downwardly, as desired, in cleaning and other operations. A wire 320 of any given source material is disposed through a central aperture 321 in the ceramic column 316 and has its end 322 extended beyond the hemispherical inner surface 323 of the cup member 315 so as to form the illustrated ball at the end during the vaporization process. The source material wire 320 rests upon a plate 324 and is grasped by springs 325 and 326. Such springs are welded to the plate 324 which, in turn, is welded to a resilient bellows 327 which surrounds a screw driving rod 328. The driving rod 328 abuts the support plate 324 at one of its ends and, at its other end (not shown) is connected to driving mechanism of any convenient type for rotating the driving rod 328 to cause rectilinear motion of the wire 320 upwardly into the cup member 315. Another resilient bellows 329 rests upon the driving piston 319 at one end and against an annular flange 330 inside the cylindrical chamber 309. Both of the bellows 327 and 329 act to seal the interior of the chamber 309 against vacuum leaks. Radio frequency coils 331 are wound about a heat concentrating cup-shaped member 332 which has an annular pointed opening 333 concentric about the end 322 of the source material wire 320 for concentrating the heating effect thereupon. The concentrating cup member 332 is mounted upon the base member 301 by means of posts, such as posts 334 which are secured to the inside surface 335 of the concentrator 332 in order to avoid shorting any of the R-F energy. Cooling coils 336 are wound within and adjacent to the concentrator cup 332 to keep their adjacent portions of such cup at a relatively cool temperature. The cooling coil conduits 337 and 338 pass through the base member 301 and out of the cylindrical chamber 309 through apertures 339 and 340 at which they are welded and are connected to a source (not shown) of coolant, such as water. A spring connector 341 grasps the source material wire 320 in electrical connection therewith and is provided with a commutator portion 342 secured to the exterior of the cylindrical portion 317 of the ceramic column 316. A spring contact 343 makes sliding electrical connection to the commutator 342 and is connected to one terminal 344 of the ionization potential source. A shield 345, composed of ceramic material, is disposed upon the head concentrator 332 and about the cup-shaped member 315, with its top surface adjacent to the end 346 of the ionizer ring 308.

Referring to FIGURES 6 and 7, which shows one of many products which may be made with the apparatus of the invention, there is seen a resistor having a support member 601 composed of a non-conductive material such as alumina, beryllia, thoria, mica-filled glass, or any high strength ceramic material, and having a smooth upper surface 602 whereby the support member 601 may function as the substrate for the practicing of the method of the present invention for depositing a monocrystal-thick polycrystalline film. The support member 601 is provided with two electrical terminals 603 and 604 spatially separated with respect to each other so as to be disposed at opposite ends of the support member 601. The terminals

603 and 604 may be composed of any convenient conductive material such as beryllium, copper or nickel, molded in place in the substrate 601. In some applications, such as those wherein the terminals may be preferably composed of other materials having greater strength or flexibility characteristics, it may be preferable to deposit a coating of such beryllium, copper or nickel on the surfaces 605 and 606 of the terminals in order to ensure a low resistance contact with the resistance film 607 to be deposited thereon. The deposition of such contact materials upon the terminal surfaces 605 and 606 may be accomplished by the mechanism of the present invention or by electro-chemical techniques, the latter being well-known in the art. In any event, such surfaces 605 and 606 of the respective terminals 603 and 604 are preferably substantially flush with the substrate surface 602. In order to ensure smoothness of that portion of the upper surface 602 of the substrate 601 on which the resistance film 607 is to be deposited, the entire surface 602 and the terminals surfaces 605 and 606 may be ground, etched or otherwise prepared for smoothness so as to prevent discontinuities in the polycrystalline film 607. Then, the substrate 601, with the terminals 603 and 604 embedded therein, is placed within the vacuum chamber previously described in connection with FIGURES 1 through 5 for the deposition thereon of the monocrystal-thick polycrystalline film 607 in accordance with the present invention. In the instant case, since the film 607 is to be a resistance element, the source material may be chosen from any standard resistance materials such as Evanohm.

Referring to FIGURES 8 and 9, there is seen a modified embodiment of a resistor made in accordance with the present invention. The substrate or support member 801, preferably in the oblong rectangular shape illustrated, is provided with shoulders 802 and 803 at opposite ends. The support member 801 may be composed of a ceramic material such as alumina or any of the other materials referred to above in connection with FIGURES 6 and 7, and may be molded, cast, or otherwise formed to have the shoulders 802 and 803. A pair of terminals 804 and 805 are substantially of an inverted L-shape and secured to the opposing ends of the support member 801 so as to completely overlap the shoulders 802 and 803, respectively. Preferably, the upper surfaces 806 and 807 of the respective terminals 804 and 805 are flush with the upper surface 808 of the substrate 801. Such upper surfaces 806, 807 and 808 may be simultaneously ground, etched or otherwise prepared to offer a smooth continuous surface for the reception of the resistance film 809 to be deposited thereon. Then, the substrate 801, with the terminals 804 and 805 secured thereto, is placed within the vacuum chamber previously described in connection with FIGURES 1 through 5 for the deposition thereon of the monocrystal-thick polycrystalline film 809. As stated in connection with the description of the resistor illustrated in FIGURES 6 and 7, the source material is chosen so that the film 809 will be a resistance element. By appropriate masking, the resistance film 809 is deposited in the oblong rectangular form illustrated particularly in FIGURE 8. Such masking may be obtained by the appropriate configuration of the aperture in the substrate holder itself, as particularly illustrated in FIGURE 4, or by any other masking technique desired. The film 809 is deposited so as to overlap the upper surfaces 806 and 807 of the respective terminals 804 and 805. The effective length of the resistance film 809 is determined by the distance between the substantially parallel opposing surfaces 810 and 812 of the respective terminals 804 and 805. The resistance of the film 809 is then predetermined by the selected width, as determined by the width of the aperture of the mask, and the thickness of the deposit, as well as the resistivity of the material chosen. As stated before, the thickness of the deposit will depend primarily upon the rate and time duration of deposit of the ions from the ion plasma generator to the substrate 801. The rate and time

duration of deposit required for a particular thickness in order to obtain a particular resistance value for the film 809 may be predetermined from a number of previous samples or may be automatically controlled by the use of apparatus and techniques involving instantaneous and continuous measurement of the resistance of the film 809 as it is deposited.

It should be noted in connection with the resistors illustrated in FIGURES 6 through 9 that such devices are ideally suited as sub-miniature types of either fixed or variable resistance elements, such as potentiometers. For example, as fixed resistors, any value of resistance may be selected by altering the relative dimensions of the spacing between the terminals, the width of the resistance film 607 or 809, the thickness of such film, and the resistivity of the material as determined by the source material chosen. For potentiometer usage, the devices illustrated may be disposed within a casing having the necessary mechanical and electrical contacts for selectively varying the position of a contact member upon the resistance film, such as a sliding or rolling contact disposed upon the top surface of the film. Because of the extreme smoothness of such upper surface, such smoothness being due to the absence of anomalies or amorphous crystalline structure, such upper surface will not abrade the potentiometer's contact element nor, as a corollary, be destroyed by repeated sliding or rolling action of such contact upon such upper surface of the film. Further, the purity and strength of a monocrystal-thick polycrystalline film causes such film to have a uniform specific resistivity throughout its entire length. In addition, the coefficient of temperature resistance is reduced by several orders of magnitude over resistance elements of the prior art, thereby ideally suiting such devices for application involving either high or low ambient temperatures as well as cycling between temperature extremes.

Referring to FIGURES 10 and 11, there is shown a potentiometer made in accordance with the use of the apparatus of the present invention. The device comprises insulating substrate 1001 which supports conductive leads 1002, 1003 and 1004. A V-shaped groove 1005 extends lengthwise along the substrate, each of the leads having enlarged head portions, as 1006 and 1007, flush with the upper surface 1010 and carried in mating depressions such as 1008 and 1009. A monocrystal thick polycrystalline film portion 1012 of resistance material is deposited so as to overlie the head ends of the leads 1002 and 1004 and the surface therebetween. Another portion of film lies coextensive with but spaced from the first portion and is deposited atop the head end of lead 1003. A conductive ball 1016 may ride along and bridge the film portions. The film portions are formed through suitable masks and are deposited on the substrate, for a period and rate of deposition as previously described. The resistance element 1012 overlaps the groove 1005. A commutator element 1015 is deposited parallel to the resistance element 1012 along the length thereof and located so as to overlay the head end 1007 of terminals 1003. The commutator element 1015 overlaps the groove 1005 in a manner identical to that of the resistance element 1012. The commutator element 1015 may be composed of copper or nickel having a gold layer on top thereof. The commutator element 1015 need not be deposited by the vacuum deposition technique of the present invention but may be deposited with any one of the well-known processes of the art such as, for example, electroless printed circuit methods.

A sphere 1016 preferably is used as the contact element between the resistance element 1012 and the commutator element 1015 because of the minimal friction encountered by a rolling sphere and the accuracy of the effectively point contact obtained thereby. The sphere 1016 may be composed of beryllium-copper, gold plated, and is mounted in an appropriate structure for continuous rolling contact with both the resistance and commutator

elements. It should be understood that the groove 1005 is narrower than the diameter of the sphere 1016 so that the substrate 1001 provides strength in backing the regions of the resistance and commutator elements 1012 and 1015 compressed by the force applied by the sphere 1016.

Referring to FIGURES 12 and 13, there is shown a semi-conductor diode, made in accordance with the apparatus of the present invention. An insulative support member 2001 is provided with two terminals 2002 and 2003 carried in depressions 2005 and 2006. Enlarged head ends 2007 and 2008 provide the relatively large contact-area surfaces 2009 and 2010 in order to obtain good contacts with the semiconductor layers 2011 and 2012, respectively to be deposited in contact therewith.

Monocrystal-thick polycrystalline layer 2012 is deposited in accordance with the method of the invention and the masking techniques previously described, to prevent the reception of the material upon any surface or portion of surface other than that upon which the semiconductor layer 2012 is to be deposited. The layer 2012 of semiconductor material of one conductivity type is then deposited upon the substrate 2001 in accordance with the previously described method. Then, by similarly appropriate masking technique, that portion of the substrate 2001 and the semiconductor 2012 upon which the semiconductor layer 2011 is to be deposited is exposed for deposition of the semiconductor layer 2011 of the opposite conductivity type. Preferably, the junction barrier, indicated at 2014 as the line between the two semiconductor layers 2011 and 2012, should have as much area as possible in view of the small size of this type of device; therefore, the semiconductor layer 2011 should cover as much of the other semiconductor layer 2012 as is practical within the considered limits of masking techniques.

Referring to FIGURES 14 and 15, there is seen a transistor, made in accordance with the present invention, which may be referred to as of the ordinary semiconductor triode type. Insulative substrate 3301 is provided with electrical terminals 3302, 3303, and 3304 having enlarged head ends 3305, 3306 and 3307, respectively, each of such head ends being flush with the upper surface 3308 of the substrate 3301. The terminal ends 3305, 3306 and 3307 present respective upper surfaces 3309, 3310 and 3311 flush with the substrate surface 3308. A first layer 3312 of semiconductor material of a first conductivity type is deposited upon the substrate surface 3308 so as to overlay the entire surface 3310 of terminal 3303. Then, a second layer 3313 of semiconductor material of a second and opposite conductivity type is deposited upon the substrate surface 3308 so as to completely overlay the upper surface 3311 of terminal 3304 and overlap a portion of the first layer 3312. A p-n junction region is formed at the common interfaces of the semiconductor layers 3312 and 3313. Then, a third layer 3314 of semiconductor material of the same conductivity type as the first layer 3312 is deposited upon the substrate surface 3308 so as to completely overlay the upper surface 3309 of terminal 3303 and overlap a portion of the second layer 3313, thereby forming a p-n junction region at the common interfaces of the layers 3313 and 3314.

The middle layer 3313 constitutes the base of the transistor, the layer 3312 may constitute the collector and the layer 3314 may be the emitter.

While the above description is limited to the use of the new apparatus for the manufacture of novel resistances and semiconductor devices, novel devices of many other characteristics may be created, as set forth in the parent application referred to at the beginning of this specification.

And while a particular embodiment of the present invention has been shown and described, it will be obvious to those skilled in the art that changes and modifications

may be made without departing from this invention in its broader aspects, and, therefore, the aim in the appended claims is to cover all such changes and modifications as fall within the true spirit and scope of this invention as defined by the claims.

What is claimed is:

1. Apparatus for the deposition of a thin film on a substrate within a vacuum chamber, comprising: a source of material to be deposited on said substrate; heating means and an ionizing element adjacent said source of material for converting said source material into a plasma having an ionized state; a first source of direct current connected between said ionizing element and said source of material, and having a potential between the first and second ionization levels of said material and having an appropriate polarity to cause vaporized atoms of said material to be ionized to the first ionization level; conductive charging means spaced from said ionizing element and beyond said substrate; a second source of direct current connected between said conductive charging means and said ionizing element, and having a polarity which will attract the ions from said ionizing means toward said charging means whereby said substrate will collect at least a portion of the attracted ions; and a magnetostatic field generating means for causing magnetic lines of flux to be disposed at said substrate for causing deposited atoms of said material to crystallize in a preferred orientation with respect to each other and said substrate.

2. Apparatus as defined in claim 1 wherein the potential of said second source of direct current has a value, in volts, of approximately 1.2 times the average atomic weight of said material, times the distance in millimeters from said ionizing element to said substrate surface.

3. Apparatus for depositing a monocrystal thick polycrystalline film upon a substrate, with the crystals in contiguous relationship to each other and with substantially uniform inclination with respect to each other and to an axis of a crystal of the film, said apparatus comprising a chamber, a substrate support in said chamber, a pump connected to said chamber for evacuating the same, a material support for source material in said chamber and remote from said substrate support, heating means adjacent said source material support for vaporizing the source material, potential applying means adjacent said source material support and including a direct current source in connection with the material support for generating an electrostatic field within which to ionize the vaporized material, electric means disposed beyond the substrate support and including a direct current source in connection with the potential applying means for creating a potential gradient to effect transport of the ionized material to the substrate on the support and means creating a magnetostatic field close to the surface of said substrate so that all of the ionized vaporized material reaching the substrate on transforming to a solid state will arrange itself with crystals in parallel alinement with respect to an axis of a crystal.

4. The apparatus of claim 3 wherein the substrate support is a perforated member above the source material support and the electric means includes positive polarity connection at the potential applying means and a charged screen at a negative polarity above the substrate support member.

5. The apparatus of claim 3 wherein the means for creating the magnetostatic field includes an electromagnetically excited yoke exteriorly of the chamber and having pole pieces adjacent the exterior wall of the chamber and cooperating pole pieces opposite the first named pole pieces internally of the chamber and close to the interior wall of the chamber, the magnetic field across said interior pole pieces traversing the substrates on said substrate support.

6. The structure of claim 3 wherein the support for the source material is a non-conductive heat resistant

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member, having a vertical channel through which the source material is threaded and the heating means is a coil connected to a source of radio frequency energy and which coil surrounds the source material protruding above the upper end of the source material support.

7. The structure of claim 3 wherein the potential applying means in connection with the electric means includes an ionizer ring connected to the positive pole of each said direct current source, said ring surrounding a space immediately above the upper end of the material support, the negative pole of each said direct current source being connected one to a conductive element of said electric means disposed above the substrate support and the other to the material support.

8. The apparatus of claim 3 wherein the heating means includes a cup-shaped member in heat transfer relationship with a source of heat energy, said cup-shaped member having its flat wall provided with an annular opening in axial alinement with the source material support, the thickness of the flat wall tapering toward the opening to concentrate the heat at said opening.

9. The apparatus of claim 8 wherein a cooling coil is placed within the cup-shaped member adjacent the skirt

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portion thereof to maintain said portion cool relative to the flat wall of the member.

10. The apparatus of claim 6 wherein the support for the source material is capped with a cup thru an open bottom of which the source material projects, said cup being surrounded by an insulating shield and extending thereabove.

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