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(54) **Title:** METHOD OF PRODUCING A SEMICONDUCTOR

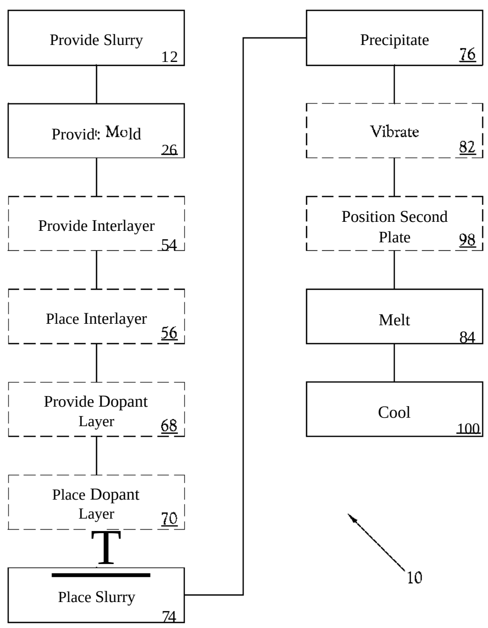

Fig.1

(57) **Abstract:** A method for manufacturing a semiconductor is disclosed. A slurry is provided which comprises a precursor powder and a liquid cover that limits oxidation of the precursor powder. A mold having an interior defining a shape of a semiconductor member is provided. The slurry is placed within the mold, and the precursor powder is precipitated from the liquid cover to deposit a layer of precursor powder within the mold. The precursor powder is then heated, melted, and then allowed to cool to form a semiconductor.

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TITLE OF INVENTION

Method of Producing a Semiconductor

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of United States Provisional Patent Application Number 61/347,904, filed on May 25, 2010; United States Provisional Patent Application Number 61/406,755, filed on October 26, 2010; and United States Provisional Patent Application Number 61/442,016, filed on February 11, 2011.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Not Applicable

BACKGROUND OF THE INVENTION

1. Field of Invention

[0003] This invention pertains to semiconductor production. More particularly, this invention pertains to a method of producing a low cost, high-efficiency, high yield semiconductor useful in numerous applications, for example in a photovoltaic cell or a light-emitting diode.

2. Description of the Related Art

[0004] The use of silicon and aluminum as precursors for making a variety of semiconductor members for use in products such as solar cells, light-emitting diodes, high energy energetic materials, and other semiconductor and ceramic applications, requires that such precursors be free of contamination with materials and elements with which these materials are naturally very reactive, such as oxygen, carbon, nitrogen, and iron. Such contamination often creates undesirable effects in the resultant semiconductor member, such as low thermal conductivity, low electrical output, low strength, poor kinetics, and poor energy output or reactivity. Because the bonds created by such contaminations are typically covalent bonds, such contaminants are difficult to remove once they have joined with the precursor. In many cases, the contaminant itself is difficult to measure and the negative effects created by the contaminant, though understood and recognized, are difficult to quantify.

[0005] As an example, in the manufacture of photovoltaic cells, commonly known as "solar cells," generally the solar cells are fabricated using a semiconductor wafer substrate using semiconductor processing techniques to form a p-n junction near a surface of the substrate. Solar radiation impinging on the surface of the substrate creates electron and hole pairs in the bulk of the substrate, which migrate to p-doped and n-doped regions in the substrate, thereby generating a voltage differential between the doped regions. The doped regions are coupled to a conductor on the solar cell to direct an electrical current from the cell to an external circuit coupled thereto. Commonly, the semiconductor wafer substrate is a silicon wafer, with the n-type junction on the surface of the silicon wafer based on phosphorous doping and the p-type junction in the body of the silicon wafer based on boron doping.

[0006] In terms of desirability for producing a low cost, high-efficiency, high yield semiconductor useful in manufacturing solar cells, it is recognized that use of solar cells in electrical energy production is attractive, in part due to the inexpensive nature of solar radiation used to fuel energy production in the solar cells. As the fuel costs associated with more conventional means of electrical energy production increase, demand for solar cells for electrical energy production also increases. However, previous methods for production of semiconductors useful in manufacturing solar cells have proven to be labor intensive, energy intensive, and materials intensive, and such previous methods have often resulted in the production of solar cells having relatively low efficiency in electrical energy production. For example, in one known method of producing a solar grade semiconductor wafer, a polycrystalline silicon material is used as the substrate. In this method, the polycrystalline silicon wafer is obtained by first placing and packing essentially pure lumps of silicon in a crucible. The crucible is loaded into a vacuum furnace that has heating elements made of graphite. The vacuum furnace heats the silicon lumps, causing them to melt. Thereafter, the melted silicon is cooled to encourage the formation of a large silicon ingot defining polycrystalline crystal formations. The crucible is commonly constructed of fused silica and, because of the processing temperature of the vacuum furnace, the fused silica partially converts to crystobalite during the melting process within the vacuum furnace. Thus, the crucible is a single use and expensive tool. The melting process also produces a polycrystalline silicon ingot having a large outer volume contaminated by impurities reacted with the melted silicon. This outer volume is cut away and discarded following manufacture of the polycrystalline ingot. Thereafter, the somewhat more pure remaining inner portion of the ingot is thin-cut into discreet polycrystalline silicon wafers using a wire saw in a diamond slurry, causing a very large additional loss of silicon, and also limiting the minimum thickness the wafer can be fabricated. The resultant polycrystalline silicon wafers can then be laminated to a conductive layer, thereby forming the solar cell as described above.

[0007] The length of the heating-cooling cycle in the above-described method is often 45-60 hours. Thus, the time associated with performing the above-described heating-cooling cycle can result in significant delays in the production process. One factor in determining the length of the heating-cooling cycle is the time required to heat the silicon feedstock sufficiently to cause it to melt. As a general rule, the smaller the initial lumps of silicon to be melted, the faster the heating and melting cycle. However, it has been found that the process of diminution of the silicon lumps into silicon granules often smears undesirable contaminants onto the surface of the resulting silicon granules. Thus, the silicon lumps used are typically very coarse, having an average size of approximately thirty (30) millimeters. Use of such coarse materials helps to preserve purity in the melted silicon. However, the packing density of the above-discussed silicon lumps in the mold is approximately thirty-five (35) percent of perfect packing, which is significantly less than ideal. Consequently, heat is not conducted efficiently through such a feedstock, and additional heating time is required. Given that (1) the heating elements are on the outside of the crucible, (2) the silicon lumps have relatively little physical contact with one another, and (3) the silicon lumps often serve to "shadow" one another from thermal radiation very heavily; most of the heating occurs by thermal radiation that is accomplished in succession, wherein a relatively exposed silicon lump is heated, and that lump then radiates heat to one or more successive relatively unexposed lumps, *i.e.,* one or more of the silicon lumps that are "shadowed." In many instances, a partial pressure of argon gas is used to assist in transferring heat to the silicon feedstock.

[0008] The above-discussed process of melting the silicon material often results in undesirable random crystal structures present in the silicon ingot, contributing to poor performance of the semiconductor polycrystalline silicon wafer. For example, in use of the polycrystalline silicon wafer for the manufacture of solar cells, such random crystal structures often result in a low efficiency in the resulting polycrystalline silicon wafer for converting sunlight into electrical energy. Furthermore, during the heating and subsequent cooling of the silicon, two impurities, *i.e.,* silicon carbide (SiC) and dissolved oxygen complexes (including silicon-oxygen complexes), are produced in the silicon feedstock. These impurities cause a reduction in the yield of usable silicon crystal wafers that can be as high as approximately forty (40) percent. Also, these impurities cause additional defects in the crystal structure that further reduce the efficiency and life of the semiconductor polycrystalline silicon wafer.

[0009] At least a few factors encourage the synthesis of these impurities. First, the high temperatures achieved in the furnace promote the oxidation of its graphite heating elements by reduction of the fused silica with which the graphite is in physical contact, thus creating a partial pressure of CO and CO2. Other components of the vacuum furnace may be composed of graphite as well, including the insulation material, and likewise, may too be oxidized. This oxidation-reduction reaction commonly yields two gases: carbon monoxide (CO) and carbon dioxide (CO_2). These gases then react with the silicon feedstock in the mold to yield silicon carbide and dissolved-oxygen complexes. Second, although rebonded fused silica is a highly refractory substance, it is permeable by carbon oxide gases *(e.g.,* CO and CO2). Thus, carbon oxide gases access the silicon feedstock by permeating the mold. Third, the packing density of the silicon lumps results in spaces that can be permeated and/or occupied by the carbon oxide gases. The surfaces of the silicon lumps that border these spaces serve as additional loci for the oxidation-reduction reaction that yields silicon carbide and dissolved-oxygen complexes. It has further been found that, in the above-referenced polycrystalline silicon production process, the melted silicon within the crucible contains approximately 350 ppm iron oxide (Fe203) in solution. At temperatures between approximately 1,100 and 1,600 degrees Centigrade of the melted silicon, crystobalite crystals precipitate within the melted silicon, thereby forcing the iron oxide into the grain boundaries of the silicon as the viscosity of the silicon lowers. Such iron oxide contaminants significantly reduce the carrier life time and efficiency of the resultant polycrystalline silicon wafer.

[OOIO] If a silicon wafer body is uniformly doped at low levels with phosphorous, use of boron to dope the surface of the silicon wafer to establish a p-type junction results in greatly increased efficiency in converting photons to electrons by the resultant solar cell. However, prior art doping technology makes this type of uniform doping of phosphorous in a solar grade silicon wafer impractical in a commercial setting. Specifically, because of the process time of the vacuum furnace and the size of the melted silicon ingot, it is impractical to direcly "dope" the melted silicon ingot to form the body of the n-type or p-type junction. Because of the limits of the doping technology, doping of the silicon is generally limited to using boron in the body of the silicon wafer to make the p-type junction and phosphorous at the surface of the silicon wafer to make the n-type junction. However, the methods of applying phosphorous to the surface of the silicon result in much larger coatings than are needed or can be achieved with boron. Finally, it must be acknowledged that vacuum furnaces generally do not create perfect vacuums, allowing atmospheric gases and potentially other gases to enter. Atmospheric gases include oxidizing agents that, as described previously, can result in the production of impurities.

[0011] A further yield loss is incurred by the sawing and slicing of the billet into wafers. Polycrystalline silicon is a relatively hard and brittle material, and thus, the operation of cutting the polycrystalline material is inherently difficult and labor intensive and results in a high mortality rate of the thin-cut silicon wafers due to fracture of the wafers during tooling and handling. In at least some instances, by the time the above-discussed contaminated outer layer is removed from the silicon ingot and the ingot is sliced down to silicon wafers having a thickness of approximately 150-200 microns, and by the time resultant fractured wafers are discarded, the yield of usable thin-cut silicon wafers on starting silicon can be as low as 10-30%.

[0012] In use of silicon semiconductor wafers in the manufacture of solar cells, while a silicon wafer of approximately 180 microns in thickness captures substantially all sunlight, a silicon wafer of approximately 40 microns still captures most sunlight, i.e., in excess of 96% of sunlight in normal conditions. The slight loss of light capture of the 40 micron wafer is more than compensated for in efficiency increases by decreased instances of recombination associated with a shorter path through the 40 micron silicon wafer. Thus, it is believed that a thinner wafer, perhaps 40 microns thick, would be optimal for use in solar cells. However, such a wafer cannot be made and handled by prior existing technology absent significant breakage of the wafer as discussed above. In light of the above, the low yield of usable silicon wafer material and the high costs per unit of solar conversion efficiency associated with manufacture of solar cells using the above-discussed process have made use of solar cells manufactured by the above-discussed process for electrical energy production in the residential, commercial, and utility sectors impractical in many applications from an economical point of view without large subsidies from governments and the like.

[0013] United States Patent Number 7,604,696 ("the '696 patent), which was issued to Carberry, describes one method of converting a silicon powder slurry into thinly molded solar grade silicon wafer. However, this and other known methods often lead to increased contamination of the resultant silicon wafers during the heating and cooling cycle. Accordingly, there is a continuing need for an improved method to produce a high-effeciency, solar cell.

[0014] Other uses for semiconductor members include the manufacture of light-emitting diodes ("LED's"). It is known that the lifetime of a semiconductor used in an LED is largely defined by its operating temperature. Specifically, the lower the operating temperature, the lower the rate of diffusion among the various thin layers of materials which enable the function of the semiconductor, such diffusion being the eventual failure mode of most semiconductors. Thus, high-purity aluminum nitride, which has a high thermal conductivity and a coefficient of thermal expansion similar to silicon, has been found to be beneficial in for use as a semiconductor in the manufacture of LED's. However, aluminum nitride of sufficient purity to achieve the requisite high thermal conductivity has traditionally suffered from a prohibitively high manufacture cost.

[0015] Two prior art processes for manufacturing aluminum nitride, carbo-thermal reduction and direct nitridation, each suffer from poor precursors and multiple processes that make it impossible to achieve low cost and low oxygen content of the aluminum nitride product. Aluminum precursors are commonly available in two forms, nanophase precursors and milled aluminum. Particles comprising a nanophase precursor have too high a surface area and too small a size to be easily useful for fabricating ceramic preforms directly. Milled aluminum is commonly available in five micron thick ribbons which are also difficult to work with in classic forming technologies for making ceramic performs. In both nanophase precursors and milled aluminum, and with both the nitriding and carbo-thermic reduction processes, the oxygen content of the finished aluminum nitride is too high to achieve sufficient purity of the aluminum nitride product for beneficial use in an LED. Likewise, silicon nitride suffers in its performance as a semiconductor largely from iron in the grain boundaries of the silicon nitride, which can only be eliminated by having a silicon powder sufficiently free of oxygen and iron as discussed above.

[0016] In light of the above, it is desirable to develop a method for manufacturing semiconductor members in which precursors are produced having a high surface area, nearly equaxed morphology, and low presence of contaminants such as oxygen, iron, nitrogen, carbon, and the like, and that such precursors have a particle size and particle size distribution suitable for forming and processing from an un-oxidized, uncontaminated state. It is further desirable that the method allow for manufacture of the semiconductor member while maintaining a heightened purity of the precursors, thus producing a high-purity finished semiconductor product.

BRIEF SUMMARY OF THE INVENTION

[0017] The present general inventive concept provides a method of producing a semiconductor having a heightened purity of the semiconductor materials. The method further allows for the production of a semiconductor with reduced waste of precursor feedstock as compared with certain prior art methods. One embodiment of the present general inventive concept can be achieved by providing a slurry comprising a precursor powder and a liquid cover to limit oxidation of the precursor powder, introducing a the slurry into a mold having an interior defining a shape of a desired finished semiconductor member, precipitating the precursor powder from the liquid cover to deposit a layer of precursor powder within the mold, melting the precursor powder within the mold, and cooling the melted precursor within the mold such that the melted precursor forms a semiconductor.

In certain embodiments, the liquid cover is a cryogenic liquid. In more discreet embodiments, the liquid cover is selected from the group consisting of liquid nitrogen, liquid argon, and liquid ethanol.

[0018] One embodiment of the present general inventive concept provides that the operation of providing a slurry can be achieved by introducing a measure of lump precursor material into a mill, introducing a measure of liquid cover into the mill, and milling the lump precursor material to form the precursor powder. In one embodiment, the lump precursor material is at least 99.9999999% pure silicon. One embodiment of the present general inventive concept provides that the operation of milling the lump precursor material includes milling the lump precursor material to a precursor powder having an average particle size at least as small as twelve microns. Another embodiment of the present general inventive concept provides that the operation of milling the lump precursor material includes milling the lump precursor material to a precursor powder having an average particle size at least as small as 300 nanometers. In one embodiment of the present general inventive concept, the mill comprises an attrition mill having internal milling surfaces fabricated from a material which is substantially non-reactive to the precursor powder. In this embodiment, the operation of milling the lump precursor material occurs absent exposure of the lump precursor material or resultant precursor powder to any material other than the liquid cover and the internal milling surfaces. In one embodiment, the internal milling surfaces of the mill are fabricated from silicon nitride.

[0019] Example embodiments of the present general inventive concept can be achieved by placing a measure of dopant in the mill along with the lump precursor material and liquid cover, where the dopant is reactive with the precursor powder to produce a semiconductor. In these embodiments, the milling operation results in mixture of the dopant into the slurry. In other example embodiments of the present general inventive concept, the slurry includes a dopant reactive with the precursor powder to produce a semiconductor. In certain embodiments, the dopant is selected from the group consisting of boron and phosphorous. Another embodiment of the present general inventive concept can be achieved by placing a dopant layer in the mold adjacent the slurry, the dopant layer being reactive with the precursor powder to produce a semiconductor.

[0020] Example embodiments of the present general inventive concept can be achieved by using a mold which is at least translucent to radiant light energy. For example, in one embodiment, the mold is fabricated from a selected from the group consisting of borosilicate glass and low iron soda lime glass. In certain embodiments, the operation of melting the precursor powder within the mold includes directing radiant light energy toward the mold, whereby the precursor powder within the mold is heated and melted by the radiant light energy. In one embodiment, the radiant light energy is generated by a plasma arc lamp.

[0021] Example embodiments of the present general inventive concept can also be achieved by using a mold which is fabricated from a material capable of being quickly heated by inductive heating. For example, in certain embodiments, the mold is fabricated from graphite. In more discreet embodiments, at least the interior of the graphite mold is covered with a material that is substantially non-reactive to the precursor powder. In certain embodiments, the operation of melting the precursor within the mold includes heating the mold with an inductive heating coil to transfer heat from the mold to the precursor, thereby melting the precursor. Example embodiments of the present general inventive concept can also be achieved by using a mold which defines a planar capillary space for encouraging wicking of the melted precursor along the planar capillary space.

[0022] One embodiment of the present general inventive concept can be achieved by introducing an interlayer between the mold and the slurry to facilitate thermal expansion and contraction of the precursor and the semiconductor along the interior of the mold. In certain embodiments, the interlayer is fabricated from a urethane polymer. In certain embodiments, the operation of precipitating the precursor powder from the liquid cover to deposit a layer of precursor powder within the mold includes vibrating the mold to encourage precipitation of the precursor powder.

[0023] Example embodiments of the present general inventive concept can be achieved by melting the precursor powder and allowing the melted precursor to cool within the mold under a cover atmosphere, the cover atmosphere limiting oxidation of the precursor powder. In certain embodiments, the cover atmosphere is comprised of argon.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0024] The above-mentioned and other features of the invention will become more clearly understood from the following detailed description of the invention read together with the drawings in which:

FIG. 1 is a flowchart showing one embodiment of the method of producing a semiconductor of the present invention;

FIG. 2 is a flowchart showing one method of providing a measure of slurry useful in performing the embodiment of the method of producing a semiconductor of FIG. 1;

FIG. 3 is a flowchart showing one method of providing a mold useful in performing the embodiment of the method of producing a semiconductor of FIG. 1;

FIG. 4 is a cross-sectional view showing a mold containing various components useful in performing the embodiment of the method of producing a semiconductor of FIG. 1;

FIG. 5 is a cross-sectional view of the mold and components of FIG. 4, showing application of radiant light energy to the mold to heat the components;

FIG. 6 is a cross-sectional view of the mold of FIG. 5, showing the finished semiconductor following heating and cooling of the mold components;

FIG. 7 is a cross-sectional view of a mold containing various components useful in performing another embodiment of the method of producing a semiconductor;

FIG. 8 is a flowchart showing another embodiment of the method of producing a semiconductor of the present invention;

FIG. 9 is a schematic side view depicting conveyance of the mold of FIG. 7 through an induction heating apparatus; and

FIG. 10 is a cross-sectional view of the mold of FIG. 7 containing the finished semiconductor following heating and cooling of the mold components.

DESCRIPTION OF THE INVENTION

[0025] A method of producing a semiconductor is disclosed herein and in the accompanying Figures. Figure 1 is a flowchart that shows one embodiment of the method of producing a semiconductor, or "method" **10.** As shown in Figure 1, the method **10** includes an operation of providing an amount of slurry **12** which is comprised of a semiconductor precursor powder that is essentially free of oxides and other undesirable impurities and a liquid cover that limits, and preferably essentially prevents, the oxidation of the precursor powder. In several embodiments, the precursor is selected from the group consisting of substantially pure silicon, substantially pure aluminum, and a combination thereof. In more discreet embodiments, the precursor is doped by alloying the precursor with materials desired in the finished semiconductor material. In one embodiment, the precursor powder component of the slurry consists essentially of particles having an average size of less than, or equal to, approximately twelve (12) microns. The advantages of this particle size are described later in this specification. In one embodiment of the present invention, the liquid cover component of the slurry prevents or nearly prevents the oxidation of the precursor powder. Accordingly, in embodiments in which the precursor powder includes silicon, the synthesis of silicon carbides *(e.g.,* SiC) is discouraged.

[0026] It will be understood that, when melting the precursor powder to form a semiconductor, a higher temperature is required to melt the precursor powder than to sinter the precursor powder. It will further be understood that, in embodiments in which the precursor powder includes silicon, sintering the precursor powder encourages the oxidation-reduction reaction that yields both silicon carbide and the dissolved-oxygen complexes, including silicon-oxygen complexes. Thus, the absence or near absence of oxides *(e.g.,* silica (S1O2)) and other harmful impurities in or on the silicon powder discourages sintering, which adversely affects the manufacture of the semiconductor. It will also be understood that the liquid cover, when combined with the precursor powder and removed just prior to melting as discussed below, protects the precursor from absorbing other gasses, including nitrogen and oxygen, which in the case of a finely divided silicon powder limits contamination of the silicon that has been shown to limit efficiency in other applications of melting silicon powders.

[0027] In one embodiment, the operation 12 of providing the slurry includes a series of operations associated with producing the slurry to be used in the method 10. Figure 2 is a flowchart illustrating one embodiment of a method of producing the slurry 12. In an initial operation, a mill is provided 14 having internal milling and containment surfaces fabricated from silicon nitride such that a material may be contained and milled within the mill with limited, and preferably no, contact to surfaces other than silicon nitride surfaces within the mill. For example, in one embodiment, an attrition mill is provided 14 having paddles defining silicon nitride outer surfaces, silicon nitride linings along the internal portions of the mill, and silicon nitride media. It will be understood that other types of grinding and milling apparatus defining other configurations of milling and containment surfaces may be employed without departing from the spirit and scope of the present invention.

[0028] A measure of lump precursor material is provided 16. In one embodiment, the provided lump precursor material consists of bulk pieces of substantially pure silicon, each bulk silicon piece being approximately 99.99% pure (hereinafter referred to as "four-nines purity"). In another embodiment, each bulk silicon piece is approximately 99.9999999% pure (hereinafter referred to as "nine-nines purity"). In another embodiment, the provided lump precursor material consists of bulk pieces of substantially pure aluminum. In yet another embodiment, the provided lump precursor material consists of a combination of bulk pieces of substantially pure pieces of silicon and aluminum. In more discreet embodiments, a measure of lump precursor material is provided 16 which has been doped by alloying the precursor material with materials desired in the finished semiconductor material.

[0029] In another operation, the liquid cover 18 is provided. The lump precursor material and liquid cover are combined and introduced into the mill. In the illustrated embodiment, combination of the lump precursor material with the liquid cover and introduction of the combination thereof into the mill occurs simultaneously as both the lump precursor material and the liquid cover are placed 20 into the attrition mill. However, it will be understood that, depending upon the specific type of mill provided 14 and the procedure for loading items to be milled therein, the chemically reactive nature of the lump precursor material and the need to protect the lump precursor material from reacting with atmospheric contaminants may require combination of the lump precursor material with the liquid cover at a time other than the time at which the lump precursor material and liquid cover are loaded into the mill. To this effect, in another embodiment, the lump precursor material and liquid cover are combined and then the combination thereof is introduced into the mill. In yet another embodiment, the lump precursor material and liquid cover are first introduced into the mill separately, and then combined within the mill.

[0030] Following the combination of the lump precursor material with the liquid cover and placing thereof into the mill **20,** the mill is activated **24,** whereupon the contents of the mill are milled to reduce the average particle size of the lump precursor material under the cover of the liquid cover. The silicon nitride milling surfaces and silicon nitride containment surfaces of the mill discourage grinding-based or attrition-based contamination of the precursor material during milling **24.** Also, in an embodiment in which an attrition mill is provided, the attrition milling **24** of the lump precursor material encourages diminution of the precursor material into powder wherein the average grain size of the precursor material is reduced to a very fine particle size, ***i.e.,*** less than 150 microns in one embodiment, and less than 300 nanometers in another embodiment. In embodiments in which the precursor material includes silicon, it will be understood that silicon particles of this approximate size have a similar lattice structure and are substantially non-conductive. In one embodiment of the present invention, the liquid cover component of the slurry consists of essentially pure water-free ethanol. In a preferred embodiment, the liquid cover consists of a cryogen, such as for example liquid nitrogen, liquid argon, or other such suitable cryogen, such that the milling **24** of the lump precursor material within the liquid cover occurs as cryogenic milling. It will be understood that such cryogenic milling of the lump precursor material results in speedier and more efficient diminution of the lump precursor material into powder, and furthermore results in easier reduction of the average grain size of the precursor material to a very fine particle size. However, it will be understood that such cryogenic milling of the lump precursor material is not necessary to accomplish the method **10** of the present invention. Furthermore, those of skill in the art will recognize other materials and combinations of materials suitable for use as the liquid portion of the slurry, and such other suitable materials may be used without departing from the spirit and scope of the present invention.

[0031] In an optional operation, prior to or during milling **24** of the lump precursor material, at least one dopant is added **22** to the mixture of precursor and liquid cover. As will be described in further detail below, the method **10** ultimately results in the precursor powder and dopant mixture being separated from the liquid cover and melted to form a semiconductor member. Thus, upon melting the precursor powder including the dispersed dopant, the resultant semiconductor member exhibits a uniformly dispersed mixture of the dopant and precursor. In one embodiment, the dopant is selected from the group consisting of boron and phosphorous. In embodiments in which the at least one dopant is added **22**, such dopant may be added to the lump precursor material, to the liquid cover, or to the combination thereof at any time prior to the conclusion of milling **24**, such that the process of milling **24** the lump precursor material and liquid cover results in substantially uniform dispersion of the dopant into the slurry. Those skilled in the art will recognize other methods for producing a slurry of a precursor powder that is essentially free of oxides and other undesirable impurities and a liquid cover, and such methods may be used without departing from the spirit and scope of the present invention.

[0032] Referring again to Figure 1, once the slurry is provided **12**, a mold is provided **26**. Figure 3 illustrates a method of providing the mold **26** used in one embodiment of the method **10** of the present invention, and Figure 4 illustrates a cross-sectional view of the mold **40**. As shown in Figure 4, the mold **40** defines a set of interior surfaces **42** conforming generally to the shape of the desired finished semiconductor member. The mold **40** is selected from a material which allows heating and melting of precursor powder placed within the mold **40**, and as will further be discussed below, the composition of the mold **40** is, at least in part, dependent upon the device to be used in heating and melting the precursor powder. For example, in certain embodiments in which radiant light energy is used, the mold **40** is selected to be at least partially transparent, or at least translucent, to the radiant light energy, in order to allow radiant light energy to pass through the mold **40** to the mold interior **42**. In other embodiments in which electricity is used to heat the precursor powder, the mold is selected to be electrically resistive of such electricity, such that electricity passing through the mold is converted to heat, thereby causing heating of the mold. Those skilled in the art will recognize other materials suitable for composition of the mold **40.**

[0033] In the illustrated embodiment of Figures 4-6, the mold **40** is selected to be substantially transparent to radiant light energy, and is composed of a material selected from the group consisting of borosilicate glass and low iron soda lime glass (hereinafter "glass"). In the embodiment of Figures 3 and 4, a first glass plate **44** is provided **28** defining an upper surface **46** conforming to an interior bottom surface of the desired mold **40.** A glass frame **48** is provided **30** which is sized to fit adjacent the perimeter of the interior bottom surface of the plate **44.** The frame **48** is joined **36** adjacent a perimeter **50** of the interior bottom surface **46,** such that the frame **48** encloses the interior bottom surface **46** and cooperates with the plate to define an interior of the mold **40** and to prevent loss of the precursor powder from the interior of the mold **40.** In an optional operation shown in the illustrated embodiment, a bonding frit **52** is provided **32** and is placed **34** between the frame **48** and the plate **44** in order to assist in joining **36** the frame **48** to the plate **44** to form the mold **40.** In another embodiment, the frame **48** and the plate **44** are integrally formed. Those skilled in the art will recognize other means for joining **36** the plate **44** and the frame **48** to form the mold **40,** and such means may be used without departing from the spirit and scope of the present invention.

[0034] In embodiments in which the method **10** is used to manufacture a semiconductor for use in the manufacture of solar cells, it is known that minimization of the grain boundaries between sides of a semiconductor wafer used in a solar cell is desirable to allow greater efficiency of conversion of photons to electrons. Thus, in an optional operation shown in the illustrated embodiment, the interior surface **42** of the mold is modified **38** to improve the process of melting precursor to form a semiconductor wafer while maintaining the purity and crystal alignment of the melted and crystallized precursor. For example, in one embodiment, the interior surface **42** of the mold is modified **38** to yield a mold interior surface **42** that (1) essentially does not react with the precursor and (2) has a crystal structure similar to that of the semiconductor to be manufactured. In one embodiment, such modification is accomplished using a method selected from the group consisting of sputtering, chemical vapor deposition (CVD), ion implantation, and metallizing. It will be understood that the purpose of the interior cavity modification **38** is to aid in orienting crystals formed within the mold **40** as melted precursor crystallizes within the mold **40.** For example, in one embodiment, the modification **38** allows the mold **40** to be differentially cooled from the bottom of the mold, thereby orienting the semiconductor crystals to grow from the bottom interior surface **46** of the mold **40** upward.

[0035] Following provision **26** of the mold **40,** and with reference to Figures 1 and 4, in several embodiments, an optional interlayer **60** is provided **54.** The interlayer **60** is placed **56** along an interior surface of the mold **40,** so as to create a forgiving layer to allow thermal expansion and contraction of semiconductor materials along the interior of the mold **40.** In one embodiment, the interlayer **60** is a polymer-type urethane of a thin cross section. However, other suitable materials will be apparent to one of skill in the art.

[0036] As discussed above, in one embodiment, an amount of dopant, such as phosphorous, boron, or other dopant, is optionally mixed directly into the fine-milled precursor to assist in creating the semiconductor. In another optional operation shown in the illustrated embodiment, a thin layer of dopant **66,** such as for example boron, phosphorous, or other dopant, is provided **68** and applied **70** to a surface of the interlayer **60** opposite the mold **40.** Similarly to the mixed dopant discussed above, the layer of dopant **66** assists in creating the semiconductor from the precursor during melting and cooling of the precursor. In one embodiment, the interlayer **60** and the dopant layer **66** are each applied within the mold **40** by chemical vapor deposition. In another embodiment, the interlayer **60** and the dopant layer **66** are each held adjacent the mold **40** by a paste or other suitable adhesive. Those skilled in the art will recognize other means which may be used to apply and secure the interlayer **60** and the dopant layer **66,** and such means may be used without departing from the spirit and scope of the present invention.

[0037] Following provision **26** of the mold **40** and application into the mold **40** of the interlayer **56** and the dopant layer **66** as described above, the slurry **72** is introduced **74** into the mold **40.** Thereafter, the slurry **72** is distributed into an even layer within the mold **40.** In certain embodiments (not shown), at least a portion of the interior surface of the mold is treated with a wetting agent to facilitate even distribution of the slurry **72** and to discourage beading of the slurry **72** within the mold **40.** In certain more discreet embodiments, only the portion of the mold **40** that is to be in contact with the slurry **72** is treated with the wetting agent. It will be understood that, in selecting the wetting agent, it is desirable to select a wetting agent that does not react with the slurry or the mold. In certain embodiments that include treatment of at least a portion of the mold with a wetting agent, the wetting agent is silicon nitride. In other embodiments, the wetting agent is silicon carbide. Those skilled in the art will recognize other suitable wetting agents which may be used without departing from the spirit and scope of the present invention. The treatment encourages the slurry to spread across a bottom interior surface of the mold, thus encouraging the formation of a semiconductor member having a uniform thickness spreading throughout the entire mold.

[0038] Referring to Figures 1 and 5, the precursor powder **78** is precipitated **76** from the slurry **72** to form a preform **80** of a semiconductor member within the mold **40** opposite the interlayer **60** from the bottom interior surface **46** of the mold **40.** In one embodiment, such precipitation **76** of the precursor powder **78** from the slurry **72** occurs by evaporation of the liquid component of the slurry **72.** In another embodiment of the present invention, as shown in the optional operation of Figure 1, the mold **40** is vibrated **82** to encourage the deposition of a uniform layer of the precursor powder **78** within the mold **40.** It will be understood that in addition to, or in alternative to, evaporation, freeze casting can be used to accomplish precipitation **76** of the precursor powder **78** from the slurry **72,** thus further limiting oxidation of the precursor powder **78.** It will further be understood that other methods and techniques may be used accomplish precipitation **76** of the precursor powder **78** from the slurry **72** to form the preform **80** without departing from the spirit and scope of the present invention.

[0039] It has been found that, in certain embodiments of the present invention in which the precursor powder **78** component of the slurry **72** consists essentially of silicon particles having an average size of less than, or equal to, approximately twelve (12) microns, the preform **80** resulting from precipitation **76** has a packing density of approximately seventy-five (75) percent, resulting in lower permeability and higher thermal conductivity of the preform **80.** This lower permeability reduces the percentage of the preform's internal surface area that is accessible to carbon oxide gases, thereby reducing the number of loci available for the oxidation-reduction reaction that yields silicon carbide and the dissolved-oxygen complexes within the precursor powder **78.** The higher thermal conductivity permits a reduction in the length of the heating-cooling cycle discussed below, further limiting the synthesis of those impurities.

[0040] As shown in Figure 5, in several embodiments, the mold **40** includes a second plate **92** which is optionally provided **96** (see FIG. 3) and positioned **98** adjacent the precursor powder **78** opposite the first plate **44** of the mold **40.** The second plate **92** is spaced apart from the first plate **44** a distance sufficient to establish a planar capillary space **94** between the first and second plates **44, 92.** In one embodiment, in which the first plate **44** lies substantially horizontally below the precursor powder **78,** dopant **66,** and interlayer **60,** the second plate **92** is disposed horizontally, resting on the substantially horizontal layer of precursor powder **78.** In another embodiment, the second plate **92** is secured to and supported by the remainder of the mold **40.** Those skilled in the art will recognize other suitable means for positioning the second plate **92** in overlapping, spaced apart relation to the first plate **44** so as to establish the planar capillary space **94,** and such other means may be used without departing from the spirit and scope of the present invention.

[0041] Following precipitation **76** of the precursor powder **78** from the slurry **72** and optional vibration **82** and placement of the second plate **92,** the preform **80** of the semiconductor is melted **84** and cooled **100** to form a semiconductor member adjacent the interlayer **60.** Referring to Figure 5, in one embodiment, the mold **40** containing the preform **80,** the interlayer **60,** and the dopant layer **66,** as described above, is placed in a cover atmosphere (not shown) which further discourages oxidation of the preform **80.** In one embodiment, the cover atmosphere is an argon gas atmosphere. A radiant energy source **88,** such as a plasma arc lamp, is provided and configured to direct an emission of radiant energy **86** toward the preform **80.** In one embodiment, melting **84** of the preform **80** is accomplished by activation of the radiant energy source **88,** thereby exposing the preform **80** to the radiant energy **86** emitted from the radiant energy source. Thereafter, the radiant energy source **88** is deactivated, and the melted semiconductor precursor is allowed to cool **100.**

[0042] As discussed above, and with reference to Figure 5, in certain embodiments the material selected for construction of the mold **40,** including, if provided, the second plate **92,** is substantially transparent, or at least translucent, to the radiant energy **86** emitted from the radiant energy source **88.** Thus, at least a portion the radiant energy **86** passes through the mold **40** and causes relatively little heating of the mold **40** in comparison to the heating of the precursor powder **78.** It has been found in melting **84** and cooling **100** the preform **80** using a plasma arc lamp that radiant energy **86** which contacts the mold **40** and is allowed to pass through the mold **40** contacts and heats an outer layer of precursor powder granules **78** forming the preform **80.** Upon exposure to the radiant energy **86** of the radiant energy source **88,** the precursor powder **78** absorbs the radiant energy **86** and very rapidly melts at temperatures in excess of 1420 degrees centigrade. However, once the outer layer of the precursor powder **78** melts into liquid, the resulting very pure liquid precursor is more transparent to the radiant energy **86** from the radiant energy source **88.** Thus, once melted, a greater portion of the radiant energy **86** passes through the melted portion of the preform **80** to adjacent particles of precursor powder **78.** In this manner, the radiant energy source **88** heats and melts the preform **80** while leaving the glass mold **40** substantially unmelted.

[0043] As discussed above, upon melting the preform **80,** the radiant energy source is deactivated, thereby discontinuing exposure of the mold **40** and the precursor **78,** dopant **66,** and interlayer **60** contained therein to the radiant energy **86** from the radiant energy source **88.** Referring to Figures 5 and 6, in embodiments in which the dopant layer **66** is provided **68** and placed **70** in the mold **40,** at an interface **90** of the melted precursor **78** with the dopant layer **66,** the dopant **66** diffuses and reacts with the precursor **78,** resulting in a boundary **93** between the interlayer **60** and the melted precursor **78** which is rich in substances helpful in improving the performance of a semiconductor. For example, in the illustrated embodiment, in which the provided dopant **66** is boron, the boundary **93** between the interlayer **60** and the melted precursor **78** is rich in silicon hexaboride, a very desirable element in the P-N junction of a solar cell for increasing solar cell efficiency.

[0044] In embodiments in which the second plate **92** is provided to form the planar capillary space **94,** upon melting the precursor **78,** the melted precursor **78** wicks throughout the capillary space **94** to substantially fill the capillary space **94** adjacent the second plate **92.** Thereafter, the melted precursor **78** and other contents of the mold **40** are allowed to cool **100** and to form a semiconductor member **110** adjacent the interlayer **60.**

[0045] It will be understood that the plasma arc lamp **88** of the present embodiment allows very quick heating and cooling and high efficiency coupling of the energy **86** from the plasma arc lamp **88** with the precursor **78,** while the material forming the mold **40** is at least partially transparent to the energy **86** from the plasma arc lamp **88.** In embodiments in which the interlayer **60** is provided, the interlayer **60** provides a mechanical stress reliever to the stresses which build up due to the expansion and contraction of the precursor **78** during heating **84** and cooling **100,** while the mold **40** remains relatively cool. In embodiments in which the second plate **92** is positioned to form the capillary space **94** in the mold **40,** the capillary wicking of the melted precursor **78** allows the preform **80** to be melted quickly and thinly, often but not necessarilly with a thickness in the range of 20 to 200 microns.

[0046] As mentioned above, in other embodiments of the method of the present invention, the operations of melting and cooling the preform are performed using other heating apparatus, and in several embodiments, the material for fabricating the mold is selected to accommodate various features of the particular heating apparatus used. Accordingly, Figure 7 illustrates a cross-sectional view of an alternate mold **40'** which is used in another embodiment of the method **10',** illustrated in Figure 8. The method **10'** employs an induction heating apparatus **104** for melting **84'** and cooling **100'** the preform **80.** Accordingly, in the illustrated embodiment of Figures 7 and 8, a mold **40'** is provided **26'** which is composed of a material easily warmed through inductive heating, such as for example graphite. As discussed above, the mold **40'** defines a set of interior surfaces **42'** conforming generally to the shape of the desired finished semiconductor member. Similarly to the embodiment discussed above, the mold **40'** includes a bottom first plate **44'** which defines an upper surface **46'** conforming to an interior bottom surface of the desired mold **40'.** A beveled circumferential lip **48'** is integrally formed along the perimeter of the upper surface **46'** of the plate **44'** and extends generally upwardly and outwardly from the plate **44',** such that the lip **48'** cooperates with the plate **44'** to define a vessel to prevent loss of the precursor powder from the interior **42'** of the mold **40'.** At least the interior surfaces **42'** of the mold **40',** and preferably all surfaces of the mold **40',**

are coated with a ceramic material **102** which is substantially non-reactive to the precursor powder. In the illustrated embodiment, the ceramic material **102** is selected from the group consisting of silicon nitride, silicon carbide, and fused quartz. Also similarly to the embodiment discussed above, a second plate **92'** is provided in a parallel, spaced apart relationship to the first plate **44'** to establish a capillary space **94'** between the first and second plates **44', 92'.** Similarly to the mold **40',** the second plate **92'** is coated with a ceramic material **102** which is substantially non-reactive to the precursor powder.

[0047] Referring to Figures 7 and 8, in the illustrated embodiment of the method **10',** the slurry is provided **12** as discussed above. Following the above-discussed provision **26'** of the mold **40',** an interlayer **60** is optionally provided **54** and placed **56** in the mold **40'** to create a forgiving layer to allow thermal expansion and contraction of semiconductor materials along the interior of the mold **40'** and a delaminating layer to assist in removal of at least one of the second plate **92'** and the mold **40'** from the finished semiconductor. The dopant layer **66** is optionally provided **68** and placed **70** in the mold **40'** along the interlayer **60** opposite the first plate **44'** of the mold **40'.** The slurry is then placed **74** into the mold **40',** precipitated **76,** and optionally vibrated **82** as discussed above to create the preform **80,** whereupon the second plate **92'** is positioned **98'** proximate the first plate **44'** to form the capillary space **94'** between the second plate **92'** and the mold **40'.**

[0048] Referring to Figures 8 and 9, following precipitation **76** of the precursor powder **78** from the slurry, optional vibration **82,** and placement of the second plate **92',** the preform **80** of the semiconductor member is melted **84'** using an inductive heater **104** to form a semiconductor member adjacent the interlayer **60.** As shown in Figure 9, the mold **40'** containing the various unfinished components of the semiconductor, including the preform **80,** is placed within a cover atmosphere (not shown) which discourages oxidation of the preform **80.** While within the cover atmosphere, the mold **40'** is conveyed by a conveyor, pushed along rails, or otherwise conveyed by a similar conveyance device **106** through a series of inductive coils **108** of the type known to one of ordinary skill in the art. As the mold **40** passes through the inductive coils **108,** the inductive coils **108** couple with the material forming the mold **40'** to rapidly heat the mold **40',** thereby also rapidly heating and melting the preform **80.** In one embodiment, the inductive coils **108** consist of a set of water-cooled inductive coils which are sized and shaped to conform closely to the shape of the combined mold **40'** and plate **92',** such that inductive coupling between the material forming the mold **40'** and plate **92'** and the inductive coils **108** is maximized. However, numerous configurations for the inductive coils **108** suitable for use in the method **10'** will be recognized by one of skill in the art.

[0049] As discussed above, following melting **84'** of the preform **80** within the mold **40',** the mold **40'** and its contents are allowed to cool **100'.** In the illustrated embodiment, such cooling **100'** of the mold **40'** is accomplished by further conveying the mold **40'** and its contents out from within the inductive coils **108,** whereupon heating **84'** of the mold **40'** ceases, and the mold **40'** and its contents are allowed to cool **100'.** Referring to Figure 10, cooling **100'** of the melted preform allows the melted precursor to form columnar growth crystalline structures, thereby forming a semiconductor member **110.** As discussed above, in embodiments in which the dopant layer **66** is provided **68** and placed **70** in the mold **40',** at an interface **90** of the melted precursor **78** with the dopant layer **66,** the dopant **66** diffuses and reacts with the precursor **78,** resulting in a semiconductor member **110** which is rich in substances helpful in improving the performance of the semiconductor member **110.**

[0050] It will be understood that, in several applications for using the semiconductor member **110** produced through the method invention **10,** the semiconductor member **110** must be capable of being removed from the mold **40.** Accordingly, in certain embodiments, at least one delaminating layer is provided within the combined mold **40'** and second plate **92'** prior to melting **84'** of the preform **80** to assist in removal of at least one of the second plate **92'** and the mold **40'** from the finished semiconductor member **110.** For example, in certain embodiments in which the interlayer **60** is optionally provided **54,** the interlayer **60** serves to enable delamination of at least one of the second plate **92'** and the mold **40'** from the finished semiconductor member **110.** However, it will be understood that additional delaminating layers may be provided without departing from the spirit and scope of the present invention.

[0051] From the foregoing description, it will be recognized by those skilled in the art that an efficient and cost-effective method of producing a semiconductor has been provided. The method of producing a semiconductor allows for the production of a semiconductor member with reduced waste of semiconductor precursor feedstock as compared with certain prior art methods. Use of the radiant energy source, or alternatively the inductive heater, as described hereinabove in the method of producing a semiconductor allows for melting and crystallization of the precursor powder to form the semiconductor member more quickly than certain prior art methods described hereinabove. Furthermore, the method of producing a semiconductor allows for the production of a semiconductor material having increased purity as compared to certain prior art methods described hereinabove.

[0052] The advantages offered by the above-discussed method include: (1) higher packing density for melting without harmful impurities; (2) quicker heating, thus resulting in less contamination by oxidation; (3) higher efficiency and yield due to shorter side-to-side path; (4) higher yield from as low as 30% to as high as 98% due to (a) less contamination by oxidation, (b) less trimming, and (c) elimination of sawing; (5) higher yield and efficiency due to the processing ability to make net shape thin wafers typically as thin as 20-50 microns, as well as thicker wafers as currently used in the range of 160-800 microns; and (6) larger wafers due to relatively unrestricted processing with regard to size, thus enabling much higher aerial yield. For instance, current technology is limited to producing a solar grade semiconductor wafer having a length of approximately 15 centimeters and a width of approximately 15 centimeters (approximately 225 cm^2). The present invention enables manufacture of a solar grade semiconductor wafer having a length of approximately one meter and a width of approximately one meter (approximately 1.0 m^2), thereby reducing or eliminating the wafer-to-wafer space losses in a finished solar cell.

[0053] While the present invention has been illustrated by description of several embodiments and while the illustrative embodiments have been described in considerable detail, it is not the intention of the applicant to restrict or in any way limit the scope of the appended claims to such detail. Additional advantages and modifications will readily appear to those skilled in the art. The invention in its broader aspects is therefore not limited to the specific details, representative apparatus and methods, and illustrative examples shown and described. Accordingly, departures may be made from such details without departing from the spirit or scope of applicant's general inventive concept.

CLAIMS

What is claimed is:

1. A method of manufacturing a semiconductor, said method comprising:

providing a slurry comprising a semiconductor precursor powder and a liquid cover to limit oxidation of the precursor powder;

introducing the slurry into a mold having an interior defining a shape of a semiconductor member;

precipitating the precursor powder from the liquid cover to deposit a layer of precursor powder within the mold;

melting the precursor powder within the mold; and

cooling the melted precursor within the mold such that the precursor forms a semiconductor.

2. The method of Claim 1 wherein said operation of providing a slurry comprises:

introducing a measure of lump precursor material into a mill;

introducing a measure of liquid cover into the mill; and

milling the lump precursor material to form the precursor powder.

3. The method of Claim 2 wherein the lump precursor material is at least 99.9999999% pure silicon.

4. The method of Claim 2, said operation of milling the lump precursor material including milling the lump precursor material to a precursor powder having an average particle size at least as small as twelve microns.

5. The method of Claim 4, said operation of milling the lump precursor material including milling the lump precursor material to a precursor powder having an average particle size at least as small as 300 nanometers.

6. The method of Claim 2 wherein said mill comprises an attrition mill having internal milling surfaces fabricated from a material which is substantially

non-reactive to the precursor powder, and wherein said operation of milling the lump precursor material occurs absent exposure of the lump precursor material or resultant precursor powder to any material other than the liquid cover and the internal milling surfaces.

7. The method of Claim 6 wherein the internal milling surfaces of the mill are fabricated from silicon nitride.

8. The method of Claim 2 further including:

placing a measure of dopant in the mill along with the lump precursor material and liquid cover, said dopant being reactive with the precursor powder to produce a semiconductor;

whereby said milling operation results in mixture of the dopant into the slurry.

9. The method of Claim 1 wherein the slurry further includes a dopant reactive with the precursor powder to produce a semiconductor.

10. The method of Claim 9 wherein the dopant is selected from the group consisting of boron and phosphorous.

11. The method of Claim 1, said liquid cover being a cryogenic liquid.

12. The method of Claim 1, said liquid cover being selected from the group consisting of liquid nitrogen, liquid argon, and liquid ethanol.

13. The method of Claim 1 wherein the mold is at least translucent to radiant light energy.

14. The method of Claim 13 wherein the mold is fabricated from a selected from the group consisting of borosilicate glass and low iron soda lime glass.

15. The method of Claim 13 wherein said operation of melting the precursor powder within the mold includes directing radiant light energy toward the mold, whereby the precursor powder within the mold is heated and melted by the radiant light energy.

16. The method of Claim 15, said radiant light energy being generated by a plasma arc lamp.

17. The method of Claim 1 wherein the mold is fabricated from a material capable of being quickly heated by inductive heating.

18. The method of Claim 17 wherein the mold is fabricated from graphite.

19. The method of Claim 18 wherein at least the interior of the graphite mold is covered with a material that is substantially non-reactive to the precursor powder.

20. The method of Claim 17 wherein said operation of melting the precursor within the mold includes heating the mold with an inductive heating coil to transfer heat from the mold to the precursor, thereby melting the precursor.

21. The method of Claim 1 further including:

introducing an interlayer between the mold and the slurry to facilitate thermal expansion and contraction of the precursor and the semiconductor along the interior of the mold.

22. The method of Claim 21 wherein the interlayer is fabricated from a urethane polymer.

23. The method of Claim 1 further including:

placing a dopant layer in the mold between the mold and the slurry, the dopant layer being reactive with the precursor powder to produce a semiconductor.

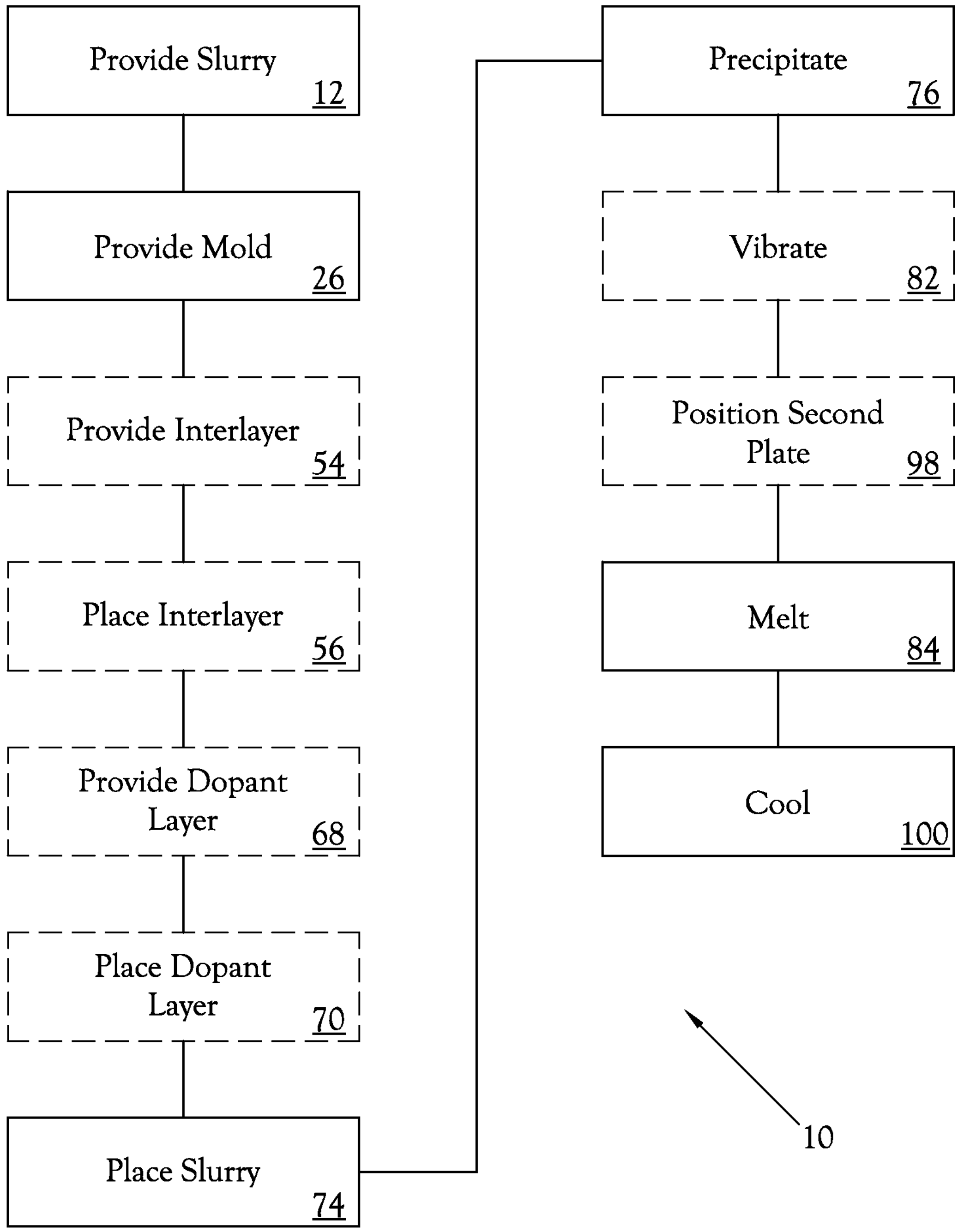
24. The method of Claim 23 wherein the dopant is selected from the group consisting of boron and phosphorous.

25. The method of Claim 1 wherein said operation of precipitating the precursor powder from the liquid cover to deposit a layer of precursor powder within the mold includes vibrating the mold to encourage precipitation of the precursor powder.

26. The method of Claim 1 wherein the mold defines a planar capillary space for encouraging wicking of the melted precursor along the planar capillary space.

27. The method of Claim 1, said operations of melting the precursor powder and allowing the melted precursor to cool within the mold occurring under a cover atmosphere, the cover atmosphere limiting oxidation of the precursor powder.

28. The method of Claim 27 wherein the cover atmosphere is comprised of argon.


Provide Slurry
12
Provide Mold
26
Provide Interlayer
54
Place Interlayer
56
Provide Dopant Layer
68
Place Dopant Layer
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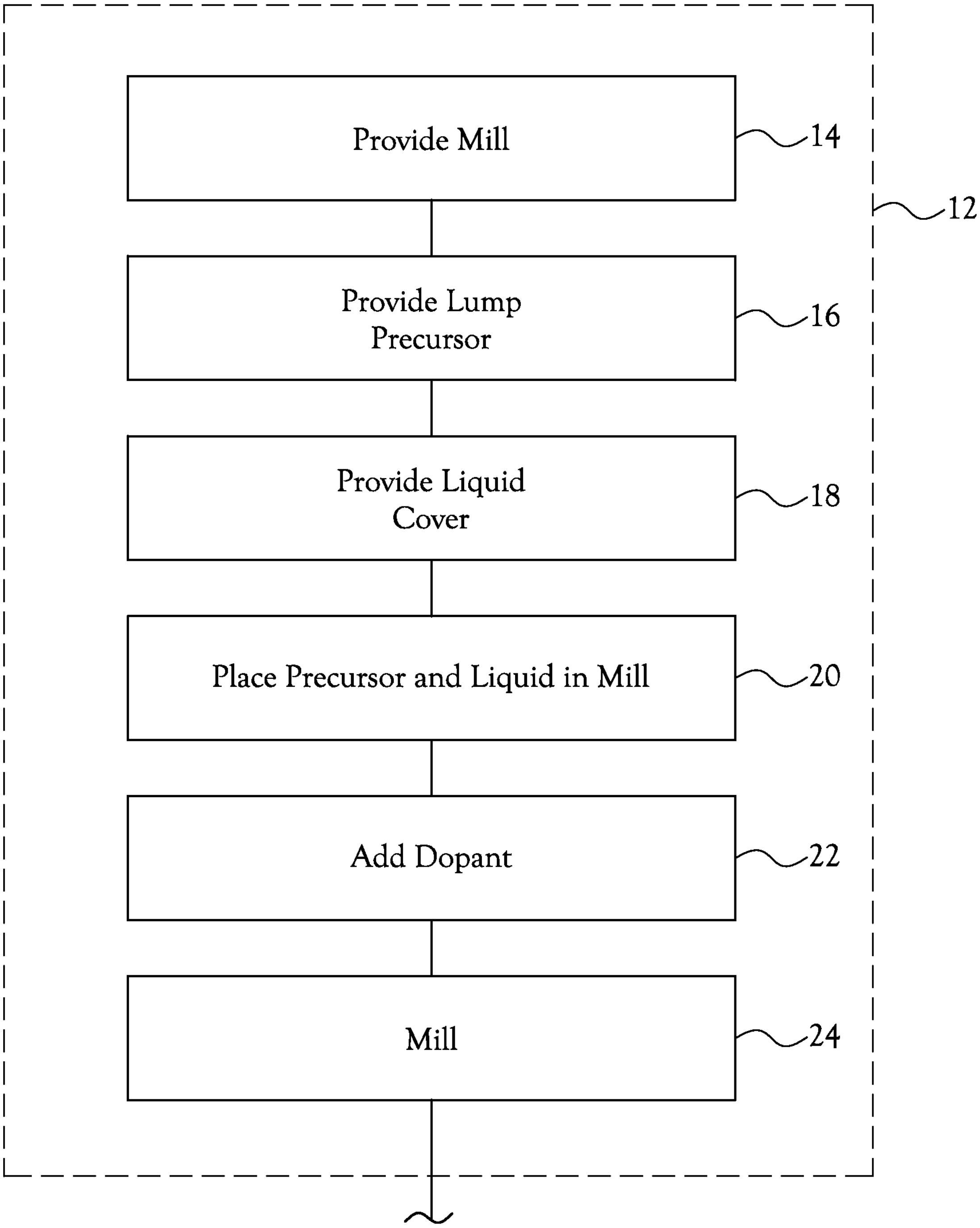
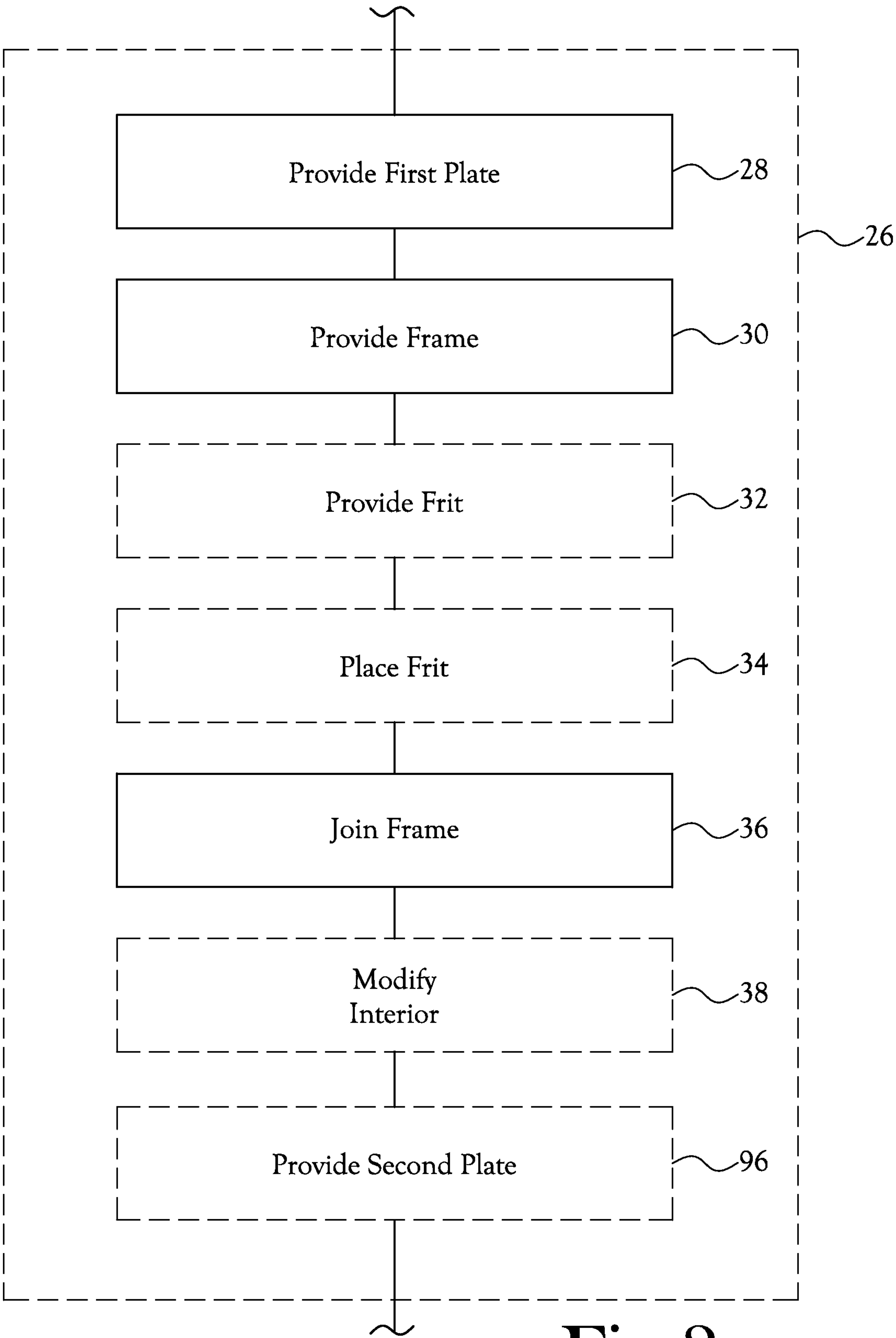
Place Slurry
74
Precipitate
76
Vibrate
82
Position Second Plate
98
Melt
84
Cool
100
10

Fig.1



Provide Mill
14
12
Provide Lump
Precursor
16
Provide Liquid
Cover
18
Place Precursor and Liquid in Mill
20
Add Dopant
22
Mill
24

Fig.2



Provide First Plate
28
26
Provide Frame
30
Provide Frit
32
Place Frit
34
Join Frame
36
Modify
Interior
38
Provide Second Plate
96

Fig.3

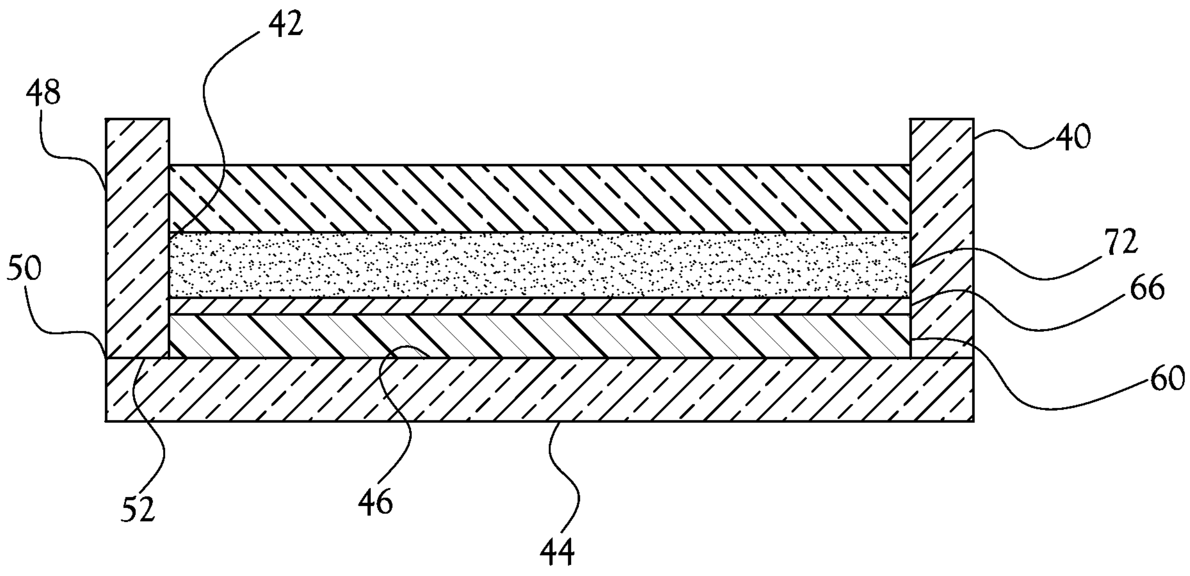
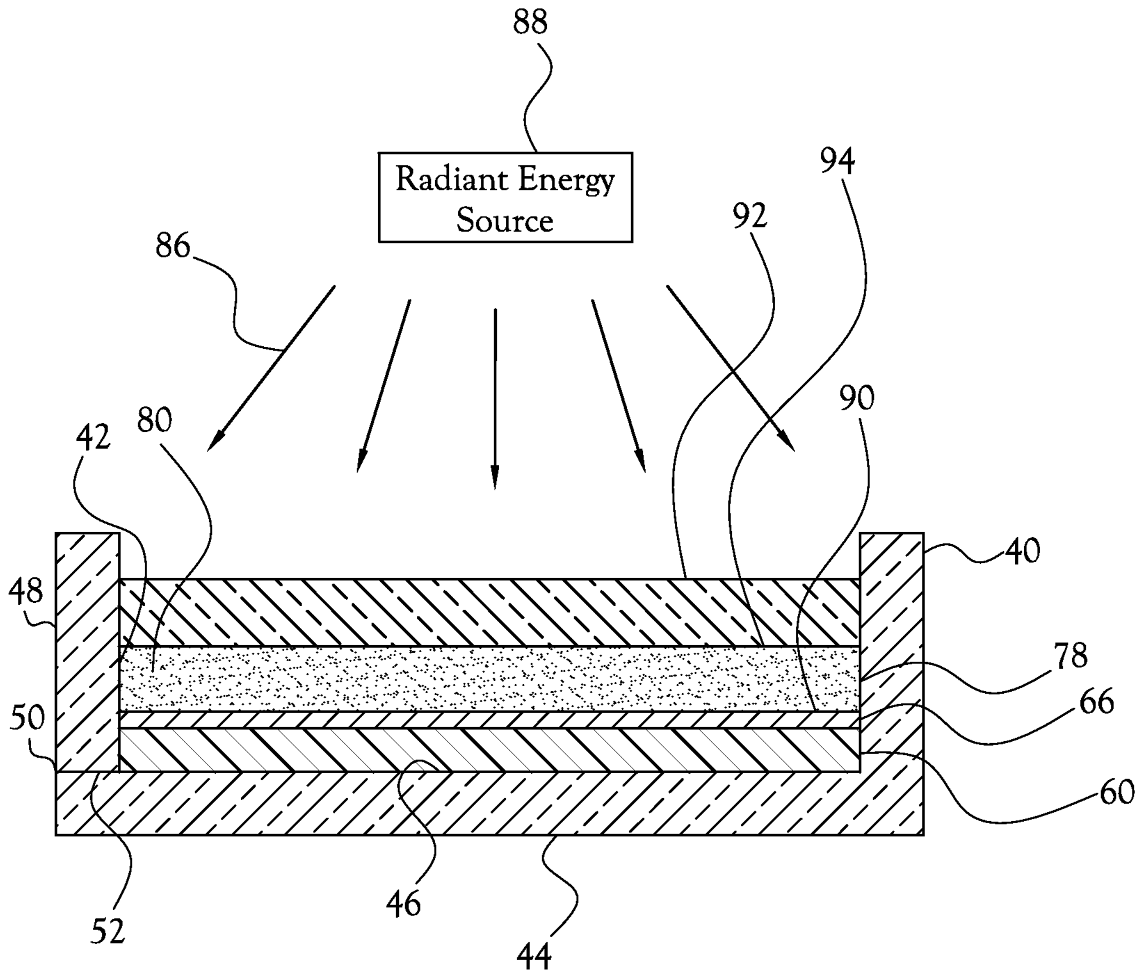


Fig.4


88
Radiant Energy Source
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92
94
90
80
42
48
40
78
66
50
60
52
46
44

Fig.5

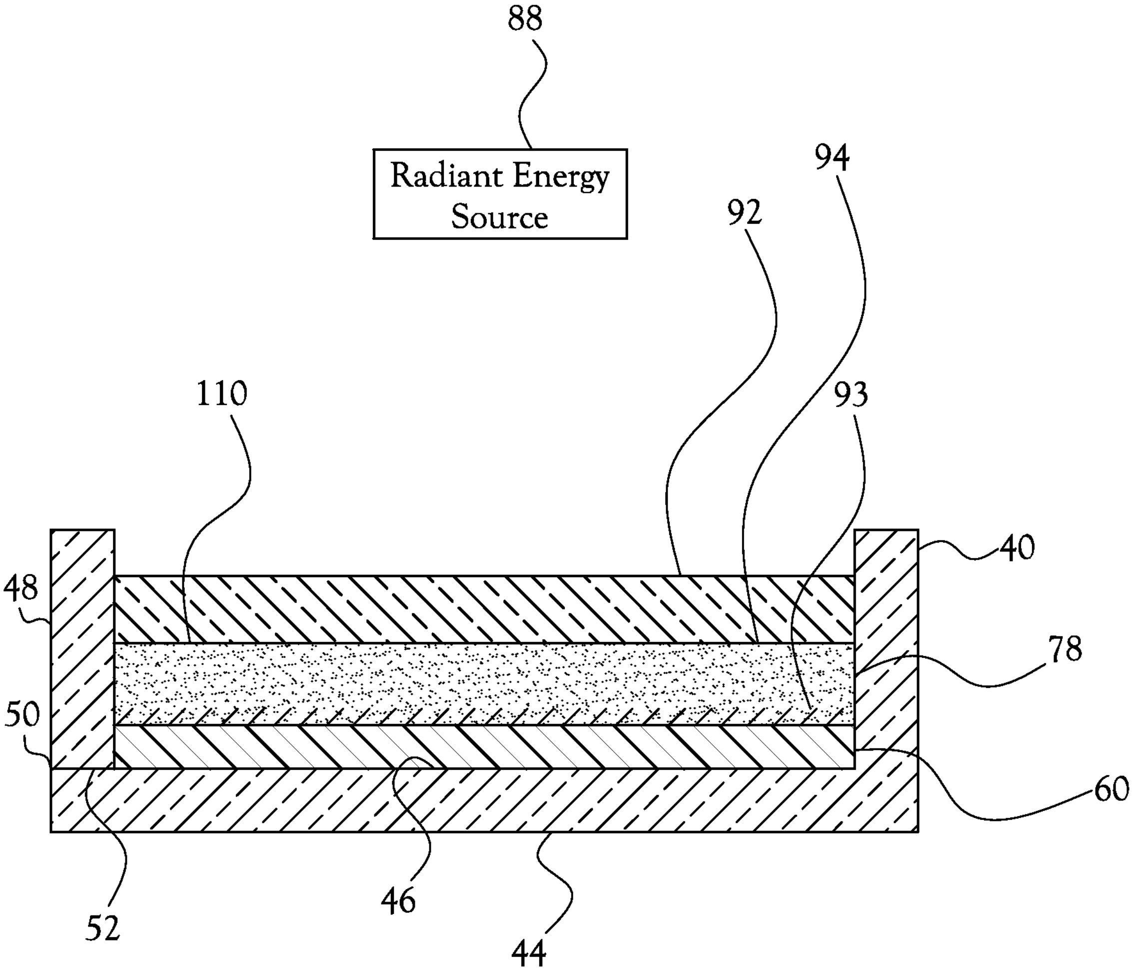

Fig.6

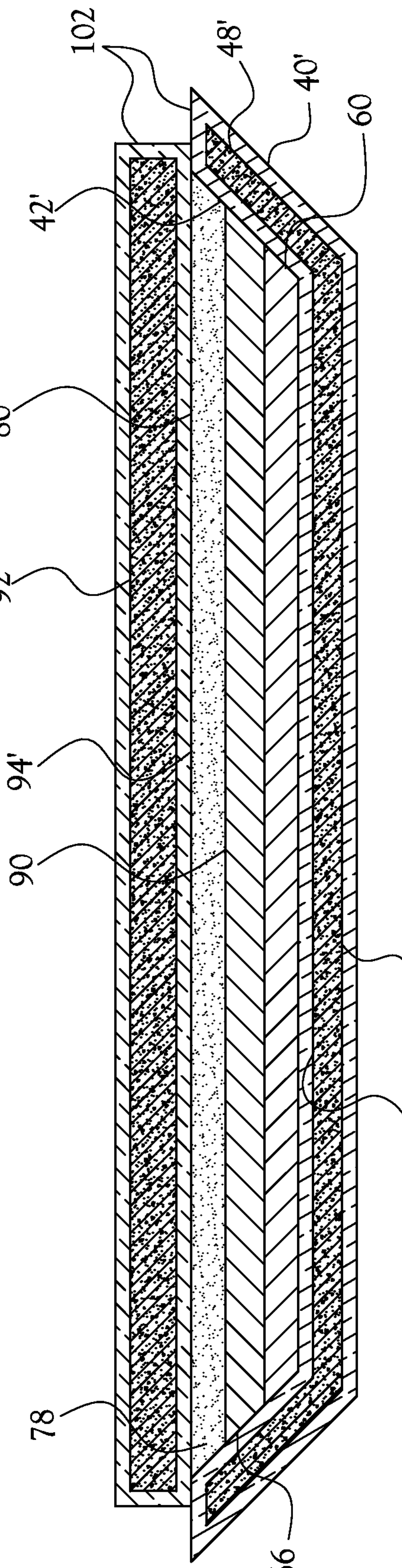

Fig.7

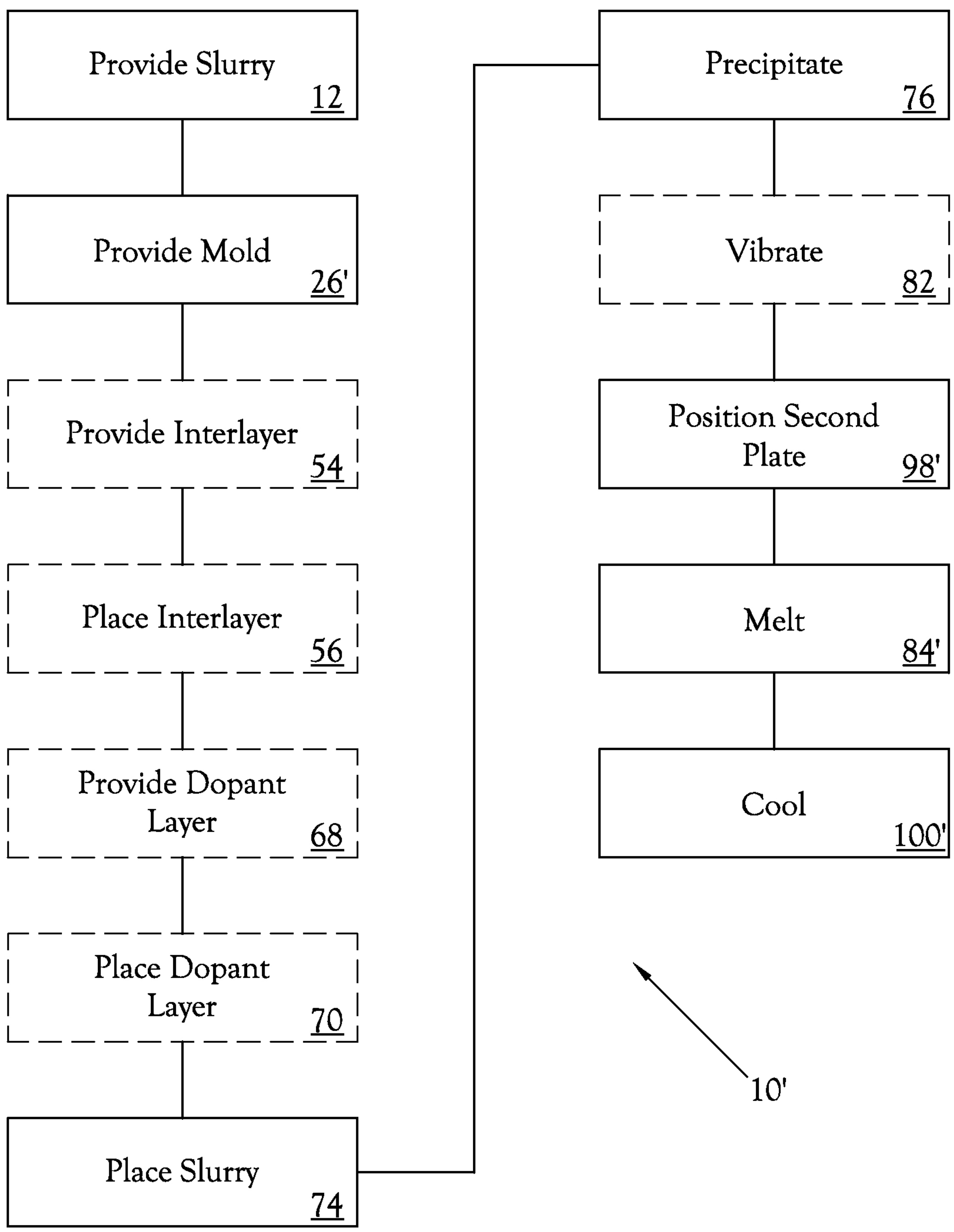
Provide Slurry
12
Provide Mold
26'
Provide Interlayer
54
Place Interlayer
56
Provide Dopant Layer
68
Place Dopant Layer
70
Place Slurry
74
Precipitate
76
Vibrate
82
Position Second Plate
98'
Melt
84'
Cool
100'
10'

Fig.8

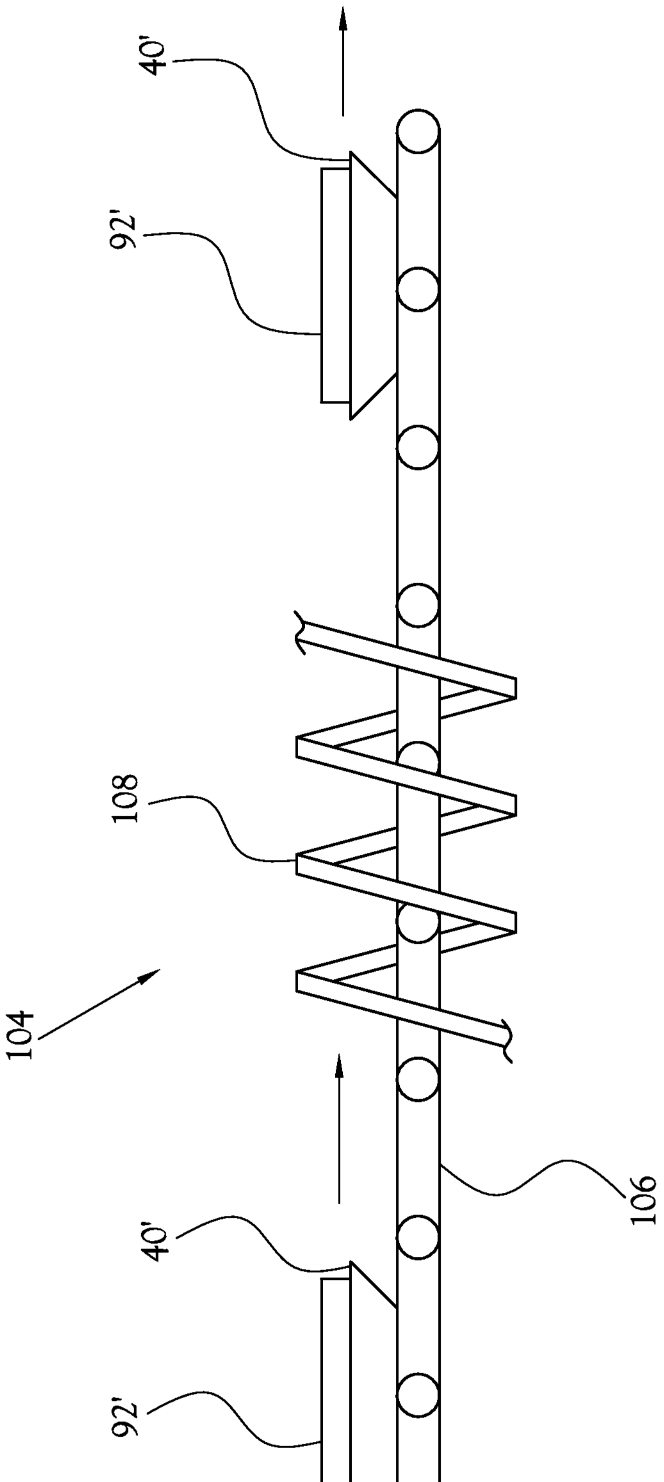

Fig.9

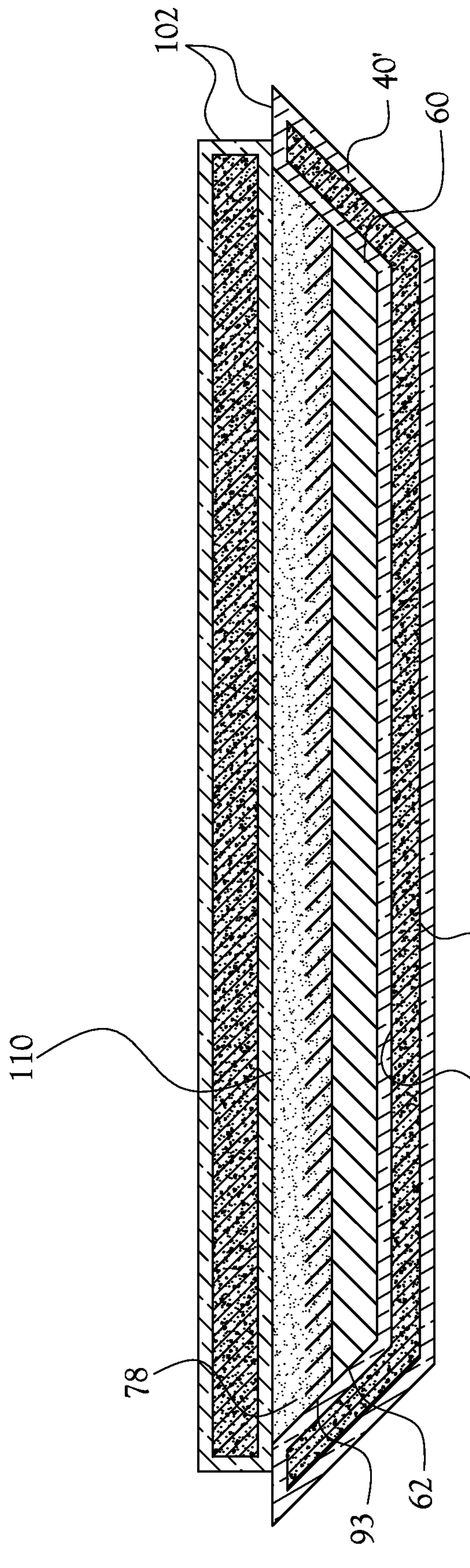

Fig.10