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(54) **PARTICLE BEAM ASSISTED MODIFICATION OF THIN FILM MATERIALS**

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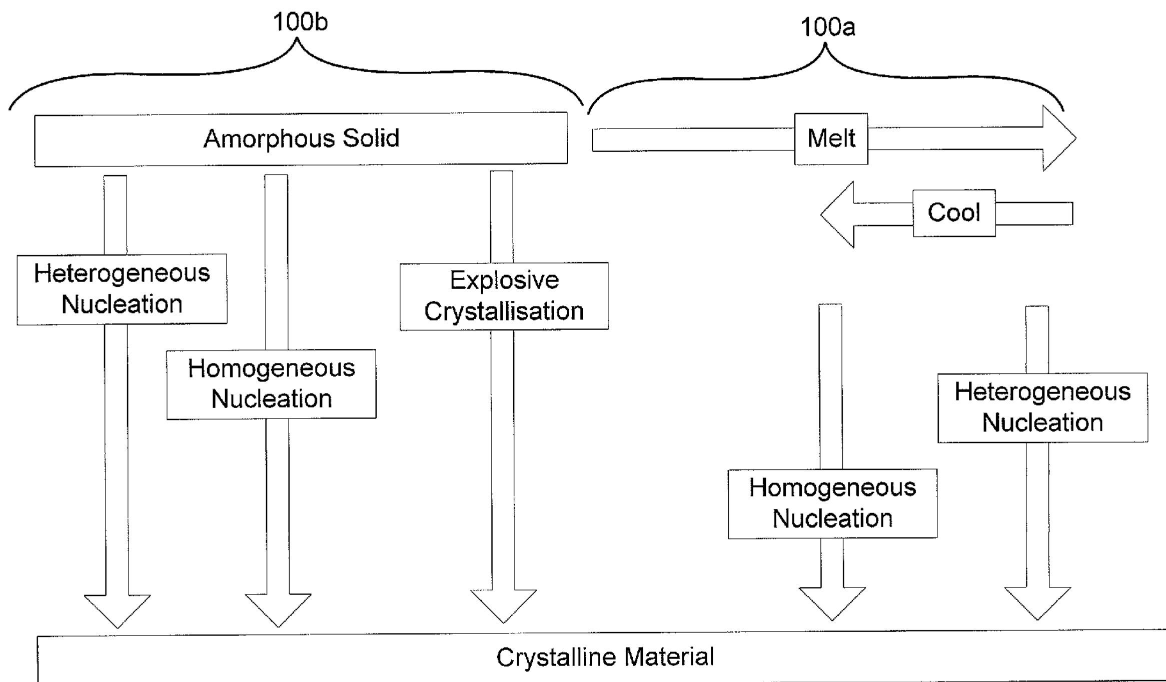
(57) **ABSTRACT**

Several examples of a method for processing a substrate are disclosed. In a particular embodiment, the method may include: disposing a substrate having an upper surface and a lower surface on a platen contained in a chamber; generating a plasma containing a plurality of charged particles above the upper surface of the substrate, the plasma having a cross sectional area equal to or greater than a surface area of the upper surface of the substrate; applying a first bias voltage to the substrate to attract the charged particles toward the upper surface of the substrate; introducing the charged particles to a region extending under entire upper surface of the substrate; and initiating, concurrently, a first phase transformation in the region from the amorphous phase to a crystalline phase.



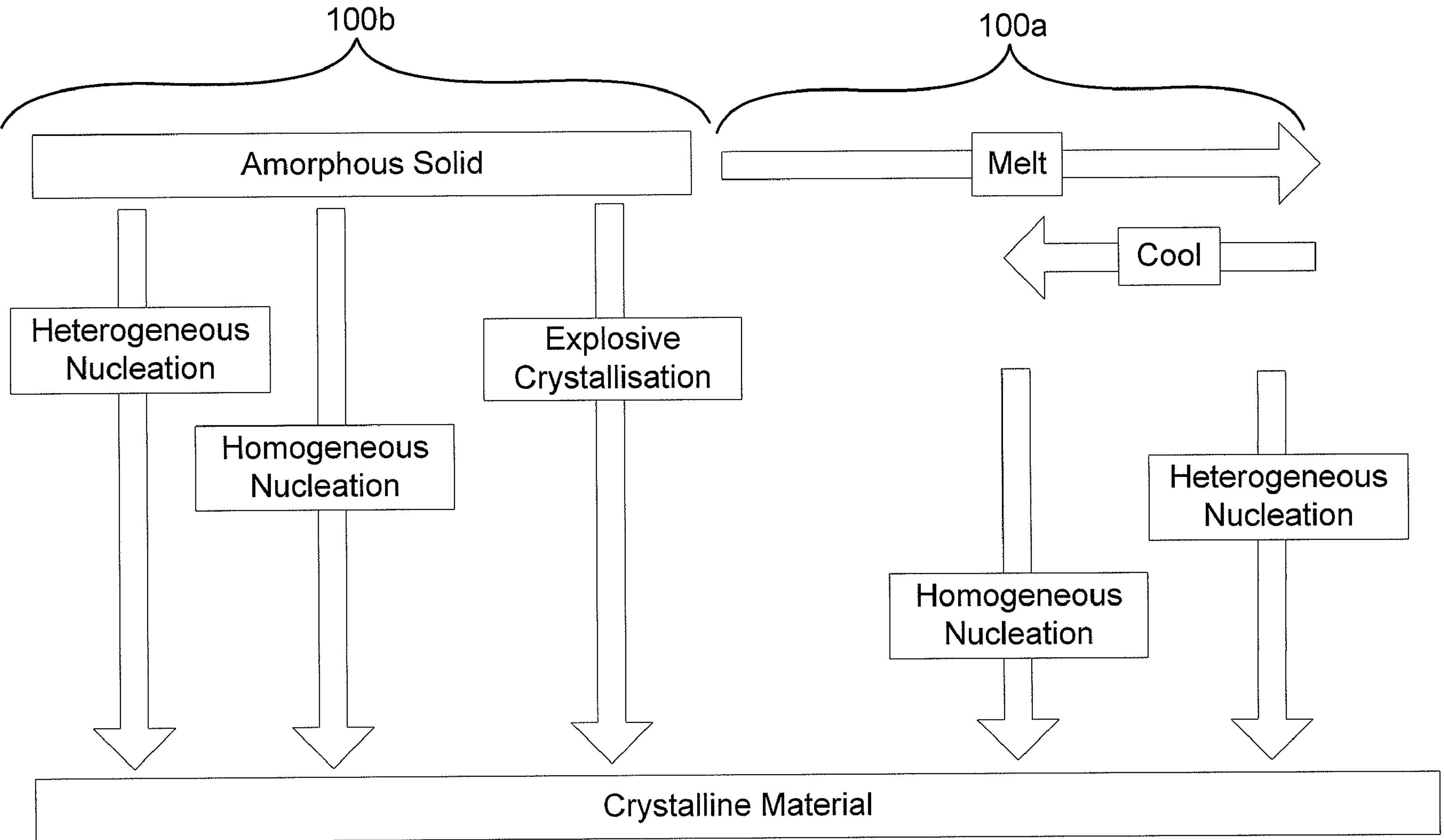


FIG. 1

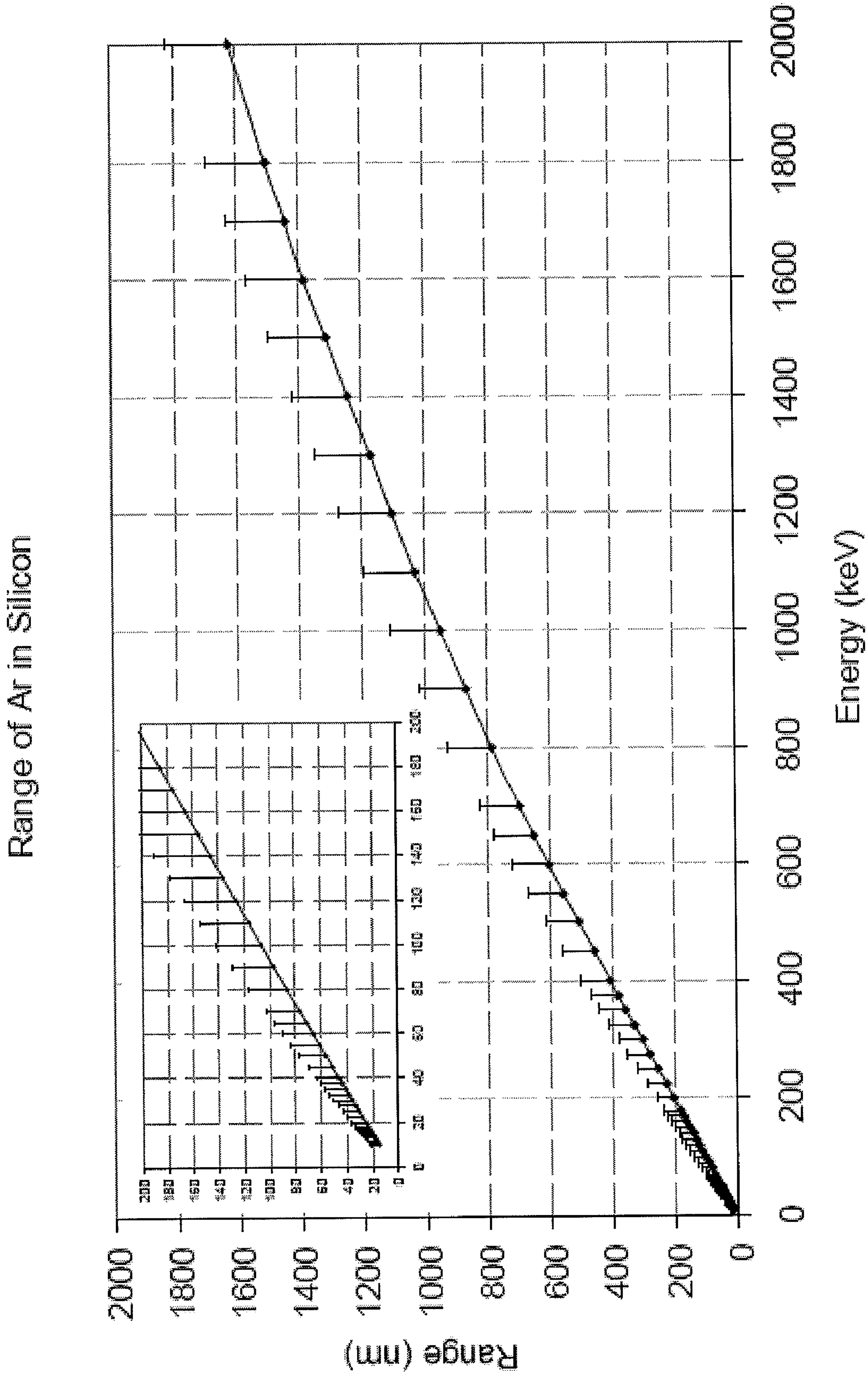


FIG. 2

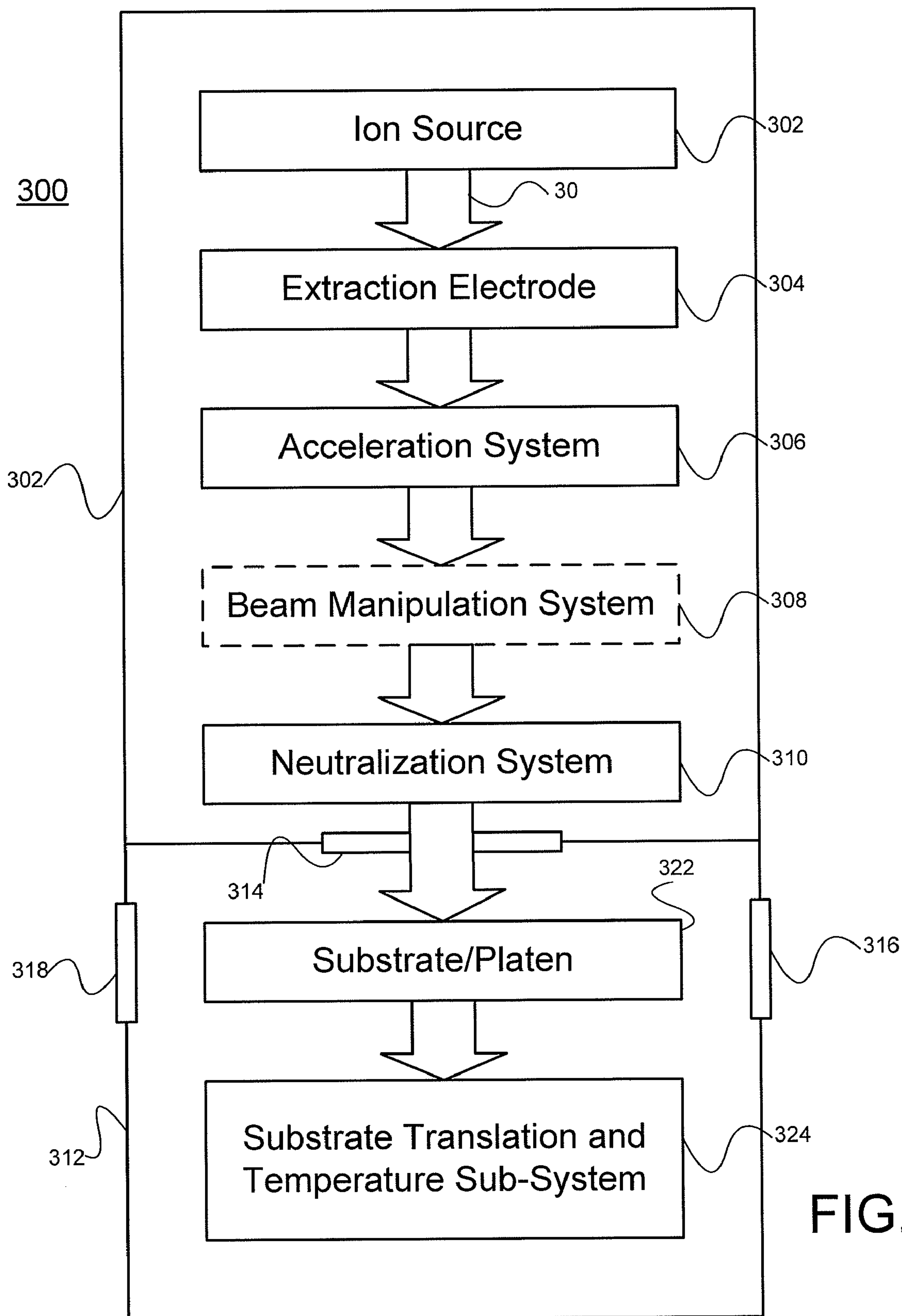


FIG. 3

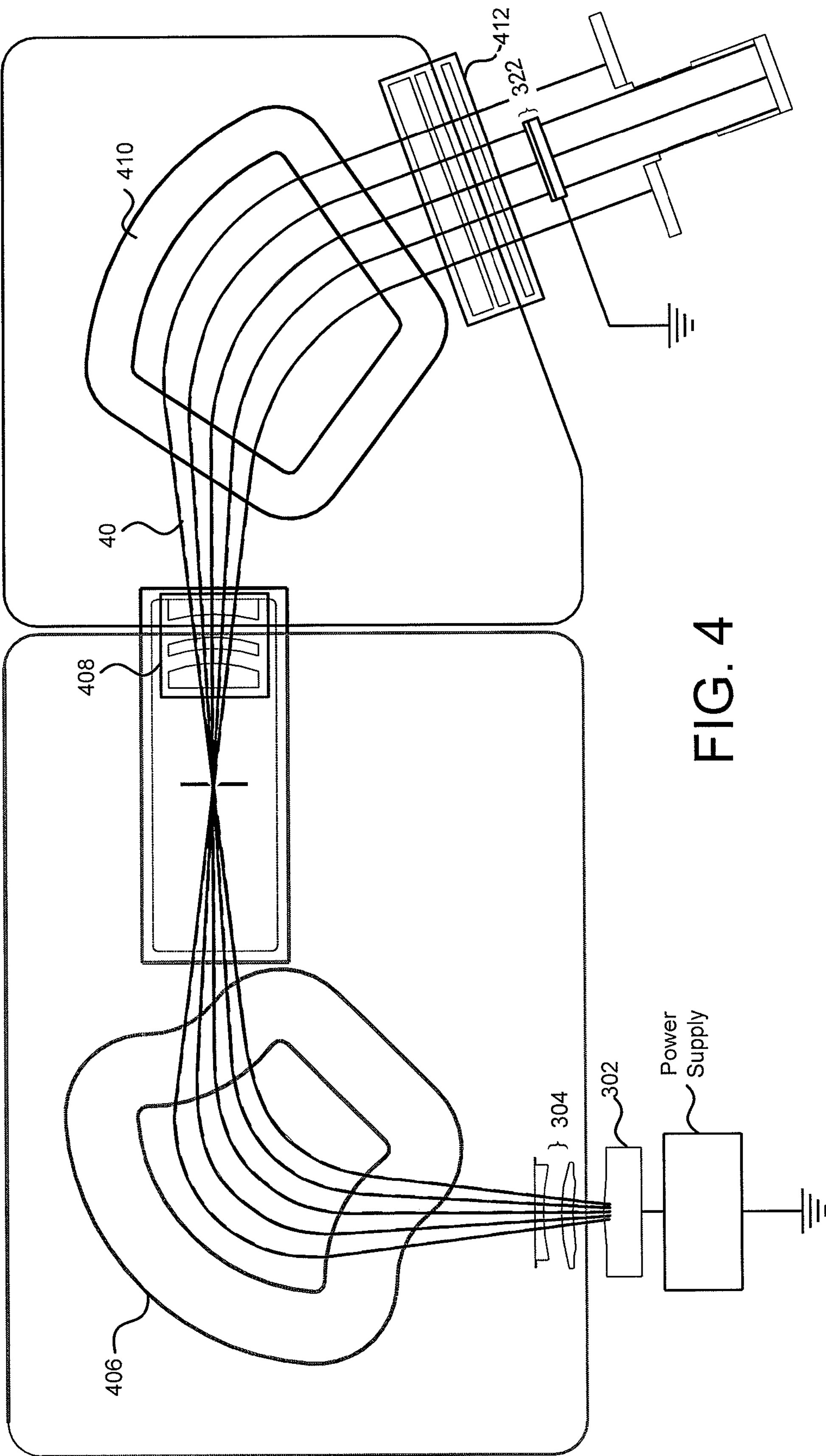


FIG. 4

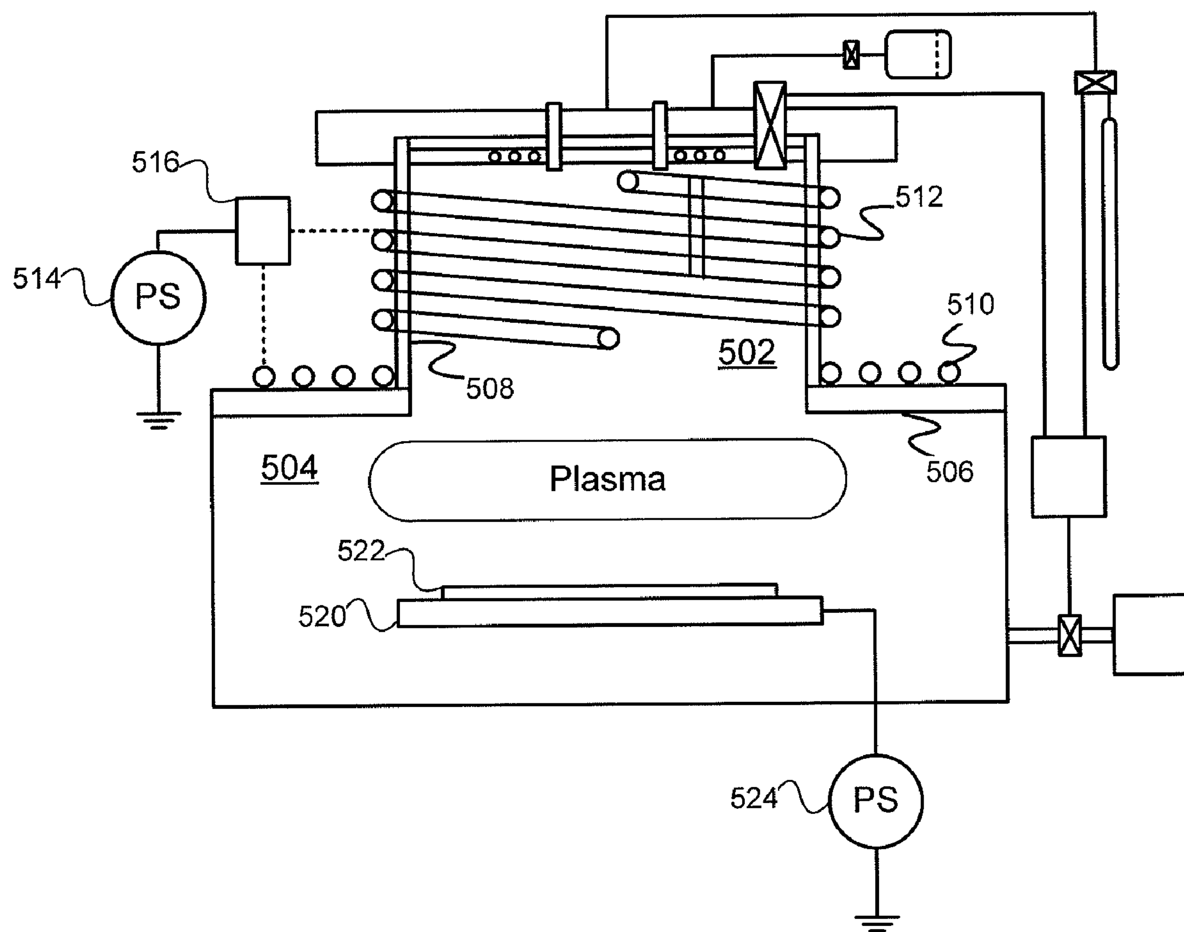


FIG. 5

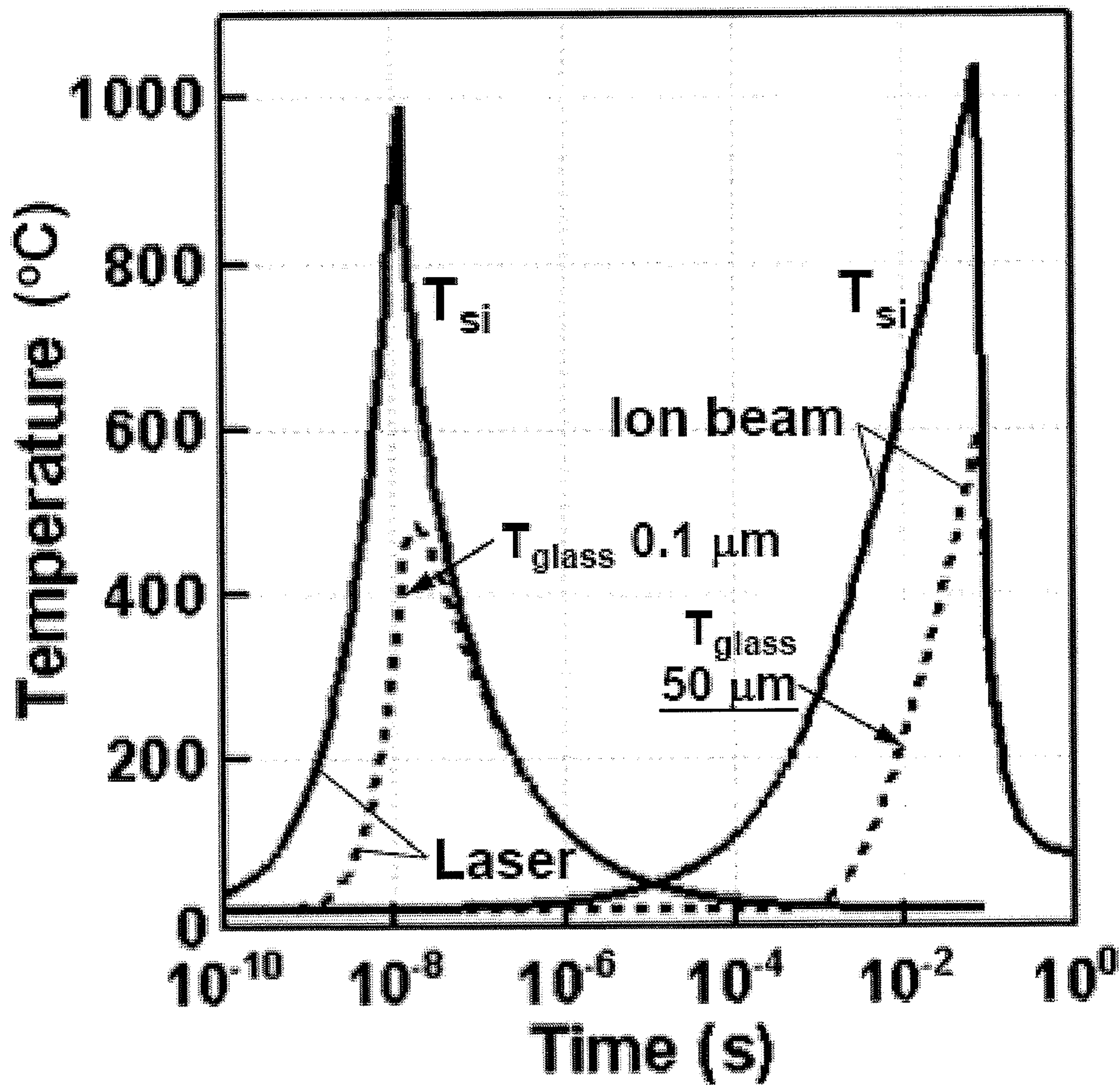


FIG. 6

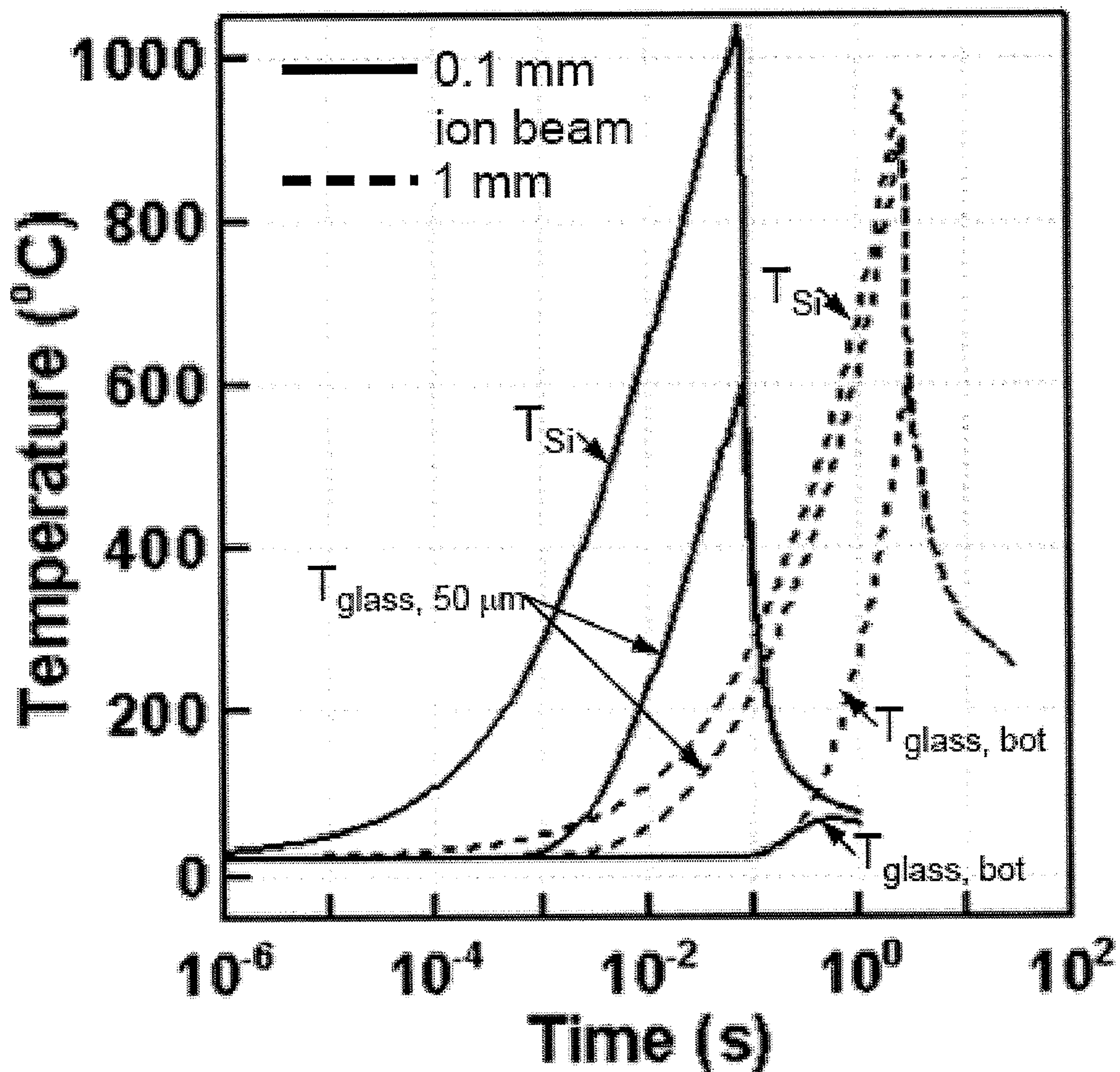


FIG. 7

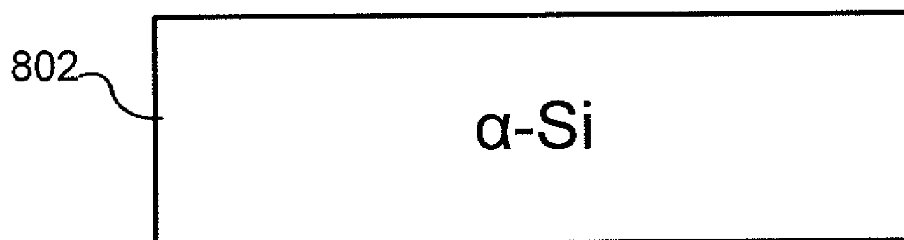


FIG. 8A

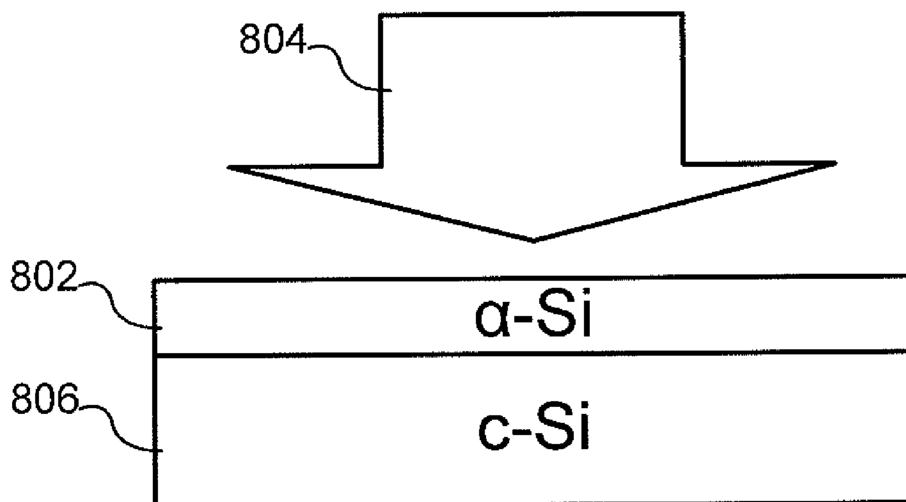


FIG. 8B

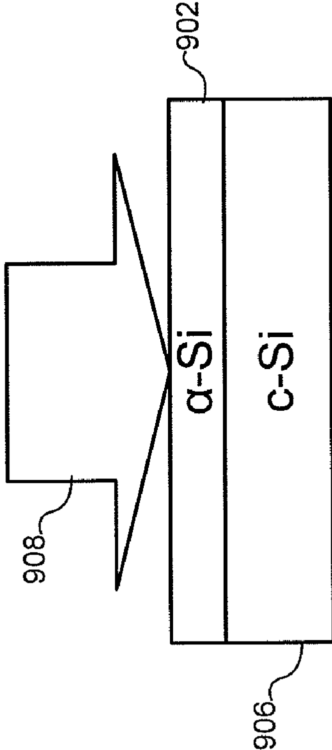


FIG. 9C

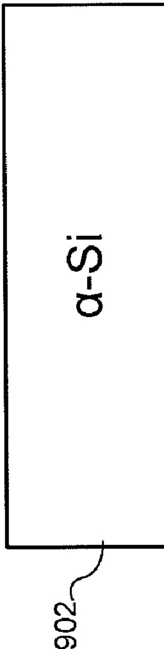


FIG. 9A

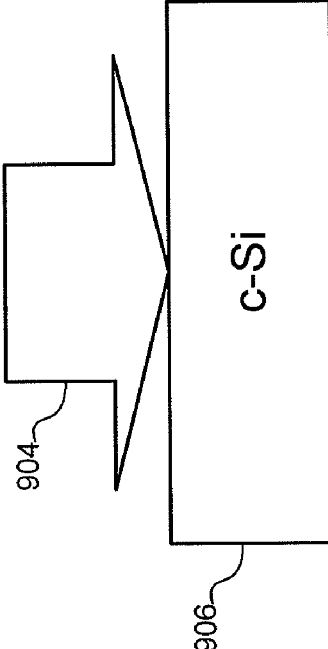


FIG. 9B

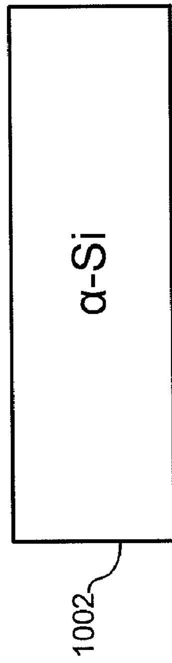


FIG. 10A

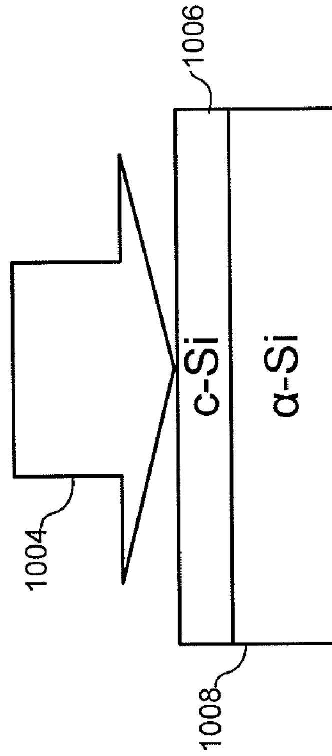


FIG. 10B

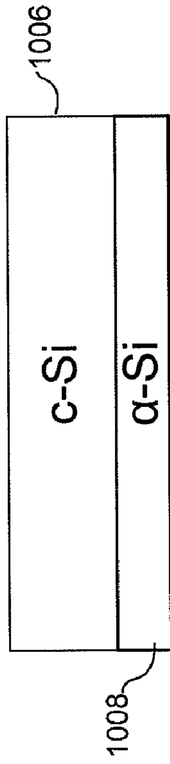


FIG. 10C

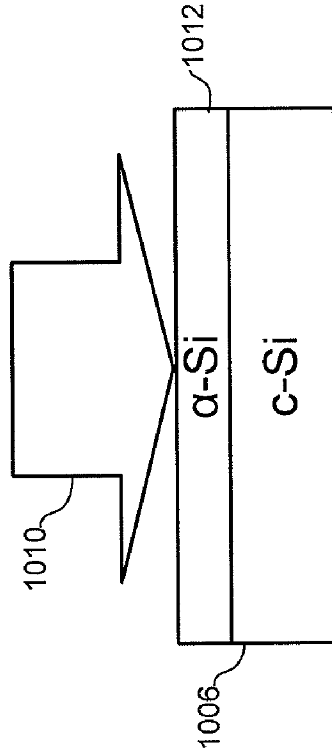


FIG. 10D

PARTICLE BEAM ASSISTED MODIFICATION OF THIN FILM MATERIALS

PRIORITY

[0001] This application claims priority to a Provisional Applications No. 60/987,629 titled "Particle Beam Assisted Modification of Thin Film Materials" and filed on Nov. 13, 2007; a Provisional Application No. 60/987,667 titled "Particle Beam Assisted Modification of Thin Film Materials" and filed on Nov. 13, 2007; and a Provisional Application 60/987,650 titled "Particle Beam Assisted Modification of Thin Film Materials" and filed on Nov. 13, 2007, each of which is incorporated in entirety by reference.

RELATED APPLICATIONS

[0002] This application is related to co-pending application Ser. No. ______ titled "Particle Beam Assisted Modification of Thin Film Materials" and filed on ______, and co-pending application Ser. No. ______ titled "Particle Beam Assisted Modification of Thin Film Materials" and filed on ______. Each of the co-pending applications are incorporated in entirety by reference.

FIELD

[0003] This disclosure relates to a system and technique for processing a substrate, more particularly, to a system and technique for forming a substrate crystalline phase.

BACKGROUND

[0004] The widespread adoption of emerging technologies such as flat panel displays (FPD) and solar cells depends on the ability to manufacture electrical devices on low cost substrates. In manufacturing FPD, pixels of a typical low cost flat panel display (FPD), are switched by thin film transistors (TFT) which may be typically manufactured on thin (~50 nm thick) films of amorphous silicon deposited on inert, glass substrates. However, improved FPDs demand better performing pixel TFTs, and it may be advantageous to manufacture high performance control electronics directly onto the panel. One advantage may be to eliminate the need for costly and potentially unreliable connections between the panel and external control circuitry.

[0005] Current FPDs contain a layer of Si that is deposited onto the glass panel of the display via a low temperature deposition process such as sputtering, evaporation, plasma enhanced chemical vapor deposition (PECVD), or low pressure chemical vapor deposition (LPCVD) process. Such low temperature processes are desirable, as the panel used to manufacture FPD tends to be amorphous and has glass transition temperature of approximately 600° C. If manufactured above 600° C., the panel may have a non-uniform or uneven structure or surface. Higher temperature tolerant glass panels such as quartz or sapphire panel exist; however, the high cost of such glasses discourages their use. Further cost reduction would be possible if cheaper, lower temperature tolerant glass or plastic panels could be used.

[0006] The low temperature deposition process, however, does not yield optimal Si film. As known in the art, solid Si has three common phases: amorphous, poly-crystalline, and mono-crystalline phases. If Si is deposited at low temperature, the deposited Si film tends to be in an amorphous phase. The channels of thin film transistors based on amorphous Si film may have lower mobility compared to those on either poly-crystalline Si or mono-crystalline Si films.

[0007] To obtain a polycrystalline or mono-crystalline Si layer, the panel may undergo further processes to convert the amorphous Si film to either polycrystalline or mono-crystalline film. To obtain a panel with poly-crystalline Si film, the panel may undergo an excimer laser annealing (ELA) process. An example of the ELA process may be found in more detail in U.S. Pat. No. 5,766,989. To obtain a panel with larger crystals, the panel may undergo a process known as Sequential Lateral Solidification ("SLS") process. An example of SLS process may be found in U.S. Pat. No. 6,322,625. Although ELA and SLS processes may result in a panel with mono-crystalline or poly-crystalline Si thin film, each process is not without disadvantages. For example, excimer lasers used in both processes may be expensive to operate, resulting in an expensive TFT. In addition, the duty cycle may not be optimum for the best conversion of amorphous Si into crystalline Si. Further, the excimer laser may have pulse-to-pulse variations and spatial non-uniformity in the delivered power which may affect the uniformity of the processes. There may also be intra-pulse non-uniformity which may be caused by for example, self-interference of the beam. Such inter-pulse and intra-pulse non-uniformity may result in Si films with non-uniform crystals.

[0008] As such, new methods and apparatus for particle processing for the cost effective and production worthy manufacture of high quality crystalline materials on low temperature substrates are needed.

SUMMARY

[0009] Several examples of a method for processing a substrate are disclosed. In a particular embodiment, the method may include: disposing a substrate having an upper surface and a lower surface on a platen contained in a chamber; generating a plasma containing a plurality of charged particles above the upper surface of the substrate, the plasma having a cross sectional area equal to or greater than a surface area of the upper surface of the substrate; applying a first bias voltage to the substrate to attract the charged particles toward the upper surface of the substrate; introducing the charged particles to a region extending under entire upper surface of the substrate; and initiating, concurrently, a first phase transformation in the region from the amorphous phase to a crystalline phase.

[0010] The present disclosure will now be described in more detail with reference to exemplary embodiments thereof as shown in the accompanying drawings. While the present disclosure is described below with reference to exemplary embodiments, it should be understood that the present disclosure is not limited thereto. Those of ordinary skill in the art having access to the teachings herein will recognize additional implementations, modifications, and embodiments, as well as other fields of use, which are within the scope of the present disclosure as described herein, and with respect to which the present disclosure may be of significant utility.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] In order to facilitate a fuller understanding of the present disclosure, reference is now made to the accompanying drawings, in which like features are referenced with like numerals. These figures should not be construed as limiting the present disclosure, but are intended to be exemplary only.

[0012] FIG. **1** is a block diagram of various mechanisms through which amorphous material may transform into crystalline material.

[0013] FIG. **2** shows a graph of the depth of Ar ions introduced to a Si substrate according to one embodiment of the present disclosure.

[0014] FIG. **3** shows block diagram of a system for processing a substrate according to one embodiment of the present disclosure.

[0015] FIG. **4** shows a block diagram of a particular exemplary system of the system shown in FIG. **3**.

[0016] FIG. **5** shows a block diagram of another system for processing a substrate according to another embodiment of the present disclosure.

[0017] FIG. **6** shows a graph comparing the temperature of a substrate irradiated with a laser beam or a particle beam.

[0018] FIG. **7** shows a graph of the temperature of a substrate irradiated with a focused particle beams according to another embodiment of the present disclosure.

[0019] FIG. **8**A-**8**B show a method that can be incorporated into manufacturing of a solar cell according to another embodiment of the present disclosure.

[0020] FIG. **9**A-**9**C show another method that can be incorporated into manufacturing of a solar cell according to another embodiment of the present disclosure.

[0021] FIG. **10**A-**10**D show another method that can be incorporated into manufacturing of a solar cell according to another embodiment of the present disclosure.

DETAILED DESCRIPTION

[0022] To overcome the above-identified and other deficiencies of existing laser-based thin film materials processing, several embodiments of particle based processing are disclosed. The particle-based processing may be advantageous as it may promote non-equilibrium processes. In addition, particle parameters may be controlled with much more precision than parameters of the laser. Examples of the particle parameters may include spatial parameters (such as beam size and current densities), particle flux (and/or beam current), particles species, and particle dose etc. . . . .

[0023] In the present disclosure, several embodiments are disclosed in context to a beamline ion implantation system and a plasma based substrate processing system such as, for example, a plasma assisted doping (PLAD) system or plasma immersion ion implantation (PIII) system. However, those of ordinary skill in the art should recognize that the present disclosure may be equally applicable to other systems including other types of particle based system. The term "particles" used herein may refer to sub-atomic, atomic, or molecular particles, charged or neutral. For example, the particles may be protons; ions, atomic or molecular; or gas clusters.

[0024] In the present disclosure, several embodiments are described in context to a substrate. The substrate may be a wafer (e.g. Si wafer) or a substrate comprising a plurality of films. In addition, the substrate may be an elemental substrate containing only one element (e.g. Si wafer or metal foil); a compound substrate containing more than one element (e.g. SiGe, SiC, InTe, GaAs, InP, GaInAs, GaInP; CdTe; CdS; and combinations of (Cu, Ag and/or Au) with (Al, Ga, and/or In) and (S, Se and/or Te) such as CuInGaSe, CuInSe2, other group III-V semiconductors and other group II-VI compounds); and/or an alloy substrate. The material contained in the substrate may be metal, semiconductor, and/or insulator (e.g. glass, Polyethylene terephthalate (PET), sapphire, and quartz). Further, the substrate may be a thin film substrate containing multiple layers (e.g. SOI). If the substrate comprises multiple layers, at least one of the layers may be a semiconducting film or a metallic film, whereas another one of the films may be an insulator. The semiconducting or metallic film may be disposed on a single insulating film or, alternatively, interposed between a plurality of insulating films. Conversely, the insulating film may be disposed on a single semiconducting or metallic film or, alternatively, interposed between multiple semiconducting or metallic films or both.

Phase Transformation

[0025] The most rapid mechanism for crystallization of thin amorphous layers is solid phase epitaxial re-growth (SPER). In SPER, amorphous Si may transform to crystalline Si by extending an underlying, pre-existing, extensive crystal layer. This scenario is commonly encountered during annealing of a surface layer of a crystalline Si wafer after it has been amorphized by ion implantation. The present disclosure relate to processing an amorphous substrate in which an extensive pre-existing lattice does not exist and which phase transformation occur via crystal nucleation prior to the growth of the crystals. Referring to FIG. **1**, there is shown a block diagram of various mechanisms through which a material without extensive pre-existing lattice may transform from an amorphous phase into a crystalline phase. As known in the art, the crystalline phase may be categorized as a poly-crystalline phase or a mono-crystalline phase. The poly-crystalline phase may sometimes be further subdivided into different categories (such as multi-, micro-, nano-crystalline etc) depending on the crystal size. However, such a distinction may not be important in the context of this disclosure, and may not be necessary to describe FIG. **1**. Accordingly, these phases may be referred herein collectively as a crystalline phase.

[0026] As illustrated in FIG. **1**, the phase transformation from the amorphous phase to a crystalline phase may occur via various mechanisms. For example, the transformation may occur via melting and solidification mechanism **10***a* and solid phase crystallization (SPC) transformation mechanism **100***b*. In the melting and solidification mechanism **100***a* and SPC mechanism, the transformation may occur via nucleation of crystallites and growth of the crystallites. In the SPER mechanism, the transformation may occur by growth on the extensive pre-existing crystal lattice.

[0027] In the melting and solidification mechanism **100***a*, energy in the form of radiation, heat, or kinetic energy, may be introduced to a portion of the amorphous substrate and melt the portion. If the condition of the molten region is adequate to induce nucleation (e.g. supercooling), crystals may nucleate as described by the classical nucleation theory. The crystals may nucleate via two schemes. The crystals may nucleate heterogeneously on pre-existing seeds. The pre-existing seeds may be grain boundaries of pre-existing crystals that did not melt upon introduction of the energy. The pre-exiting seeds may also be the boundary between the molten region and adjacent solid region. If the pre-existing seeds are absent, the crystals may nucleate homogeneously. Upon nucleation, the crystals may grow until the growth is halted.

[0028] In the solid phase transformation mechanism **10***b*, the phase transformation may occur despite the absence of the melting. For example, crystals may nucleate in the region introduced with energy, and the nucleation may be followed

by the growth of the nucleated crystals. As in the case of the melt process, nucleation during SPC can occur heterogeneously if pre-existing seeds exist, or homogeneously if such seeds are absent.

Particle Assisted Processes

[0029] In the present disclosure, particles may be introduced to a substrate to induce the phase transformation. The phase transformation may be that from the amorphous phase to one of the polycrystalline and/or mono-crystalline phases. In addition, the phase transformation may occur via nucleation and growth of the crystals. To induce the transformation, the particles may be introduced near the upper surface of the substrate, the lower surface of the substrate, or a region between the upper and lower surfaces, or a combination thereof. If the substrate comprises two or more different materials, the particles may be introduced to a region near the interface of the different materials.

Particle Species

[0030] Numerous types of particles may be introduced to induce the phase transformation. For example, the particles that are chemically and/or electrically inert with respect to the substrate may be used. However, chemically and/or electrically active material may also be used. As noted above, the particles may be charged or neutral sub-atomic particles, atomic particles, or molecular particles, or a combination thereof. In some embodiments, molecular particles are preferred. In other embodiments, cluster particles are preferred. Molecular and cluster particles may be preferred as they may be introduced to the substrate at much higher dose and energy. In particular, molecular and cluster particles introduced to a substrate may disintegrate on impact, and the kinetic energy of the particles may be shared in the ratio of the atomic masses of the particle atoms. The overlapping collision cascades may achieve result similar to introduction of atomic particles at much higher dose rate. Due to their greater mass, the molecular particles may also be introduced to the substrate at much higher energy. The generation of atomic and molecular species in implanters, PLAD and PIII will be familiar to those skilled in the art. A detailed description of the generation of cluster particles may be found in U.S. Pat. No. 5,459,326, which is incorporated in entirety by reference.

[0031] The choice of the particles introduced to the substrate may also depend on the effect of the particles on the substrate. Some characteristics and illustrative examples are shown in Table 1.

TABLE 1

Some possible choices of ion species

Characteristic	Example species
Electrically inactive in silicon	Ge, Si, C, F, N H, He, Sn, Pb, hydrocarbon molecules, molecules containing C and two or more other elements, hydrides of silicon such as tetra-silane, molecules containing Si and two or more other elements
Dopants	B, P, As, Sb, In, Ga, Sb, Bi,
Shallow Junction Co-implant species	C, F
Amorphizing	Noble Gases (including He, Xe), Ge, Si
Strain producing	Ge, C
Bandgap engineering	Yb, Ti, Hf, Zr, Pd, Pt, Al
Passivating	H, D
Defect Pinning	N
Crystallization catalysts	Ni, metals

Depth and Energy

[0032] When the particles are introduced to the substrate, the kinetic energy of the particles may be transferred to the substrate. The magnitude of the transferred kinetic energy may depend on the size, mass, and energy of the particles. For example, heavy ions introduced to a substrate may experience more nuclear stopping than lighter ions. When the particles lose their kinetic energy via the nuclear stopping mechanism, the mechanism tends to form defects such as, for example, dangling bonds, vacancies, and di-vacancies, whose presence may enhance the crystallization process. At the same time, kinetic energy transferred to the substrate via electronic stopping may cause crystallization.

[0033] Depending on the energy of the particles, the location of the particles delivery, and the properties of the substrate (e.g. thermal conductivity, heat capacity and melting temperature of the substrate), nucleation of crystals may be initiated at the upper surface of the substrate; the lower surface of the substrate; the region between the upper and lower surfaces; or near the interface of different materials. Thereafter, the phase transformation may continue in a direction away from the location where the transformation is initiated.

[0034] Unlike the radiation based phase transformation, energy deposited to the substrate via the particle introduction may peak at the surface or, alternatively, below the surface. In addition, the particles may be introduced to the substrate at a constant energy. Alternatively, the particles may be introduced at varied energies. For example, the energy of the particles introduced to the substrate may change while the particles are being introduced. The change in the energy may occur continuously or in a sequence. If a beam-line particle system is used, the particle energy may be changed during the particle introduction using acceleration or deceleration voltage associated with beam-line systems described herein. If PLAD, PIII, or other plasma based system is used, the energy may be changed during the introduction by varying the voltage applied to the substrate.

[0035] Referring to FIG. **2**, there is a graph showing depth and energy of particles introduced to a substrate, according to one embodiment of the present disclosure. In the present embodiment, Ar ions are implanted into Si thin film. As shown in FIG. **2**, the points joined by the line represent the average range of the Ar ions and the vertical error bars represent the straggle in depth. The total range of all ions can then be estimated by the sum of the average range plus a multiple (one or more) of the straggle. If the Ar ions were required to be contained within a surface layer of Si of known depth, the maximum energy may be estimated from this curve. The inset chart is a larger representation of the low energy scale of the main chart.

Spatial and Temporal Profile

[0036] In addition to the energy, the spatial and temporal profile of the particles may be controlled. For example, the

particles may be introduced as a particle beam, and the beam may have constant or varied beam current density (i.e. number of particles in a predetermined area for a predetermined time). The current density may be adjusted by changing the particle current and/or beam size; the beam dwell time by controlling the beam and/or substrate scanning speeds and/or pulse length; and the beam duty cycle (e.g. time between beam pulses or return time if the beam and/or substrate are scanned).

[0037] In the present disclosure, the particles may be introduced to the substrate continuously or periodically in sequence. If the particles are introduced as a particle beam, the beam may have various shapes. For example, the particles may be introduced as a ribbon beam or a spot beam. The ribbon beam may have a ribbon shape or a shape where the dimension of the beam along one direction is larger than along another direction. Such a ribbon beam may be wider than the substrate or, alternatively, narrower than the substrate. The spot beam, meanwhile, may have a dimension smaller than the substrate. If used, the spot beam may be scanned, either magnetically or electrostatically at a rate of approximately 100-1000 Hz, to resemble the ribbon beam.

[0038] If the cross section of the beam, whether a ribbon beam or a spot beam, is smaller and does not cover the entire surface area of the substrate, the beam may be additionally scanned relative to the substrate. For example, the beam may be scanned along 2 directions, along the width direction and length direction, such that the particles may be introduced to the entire surface of the substrate. In the present disclosure, such scanning may be achieved by translating the substrate along the length and width directions relative to a stationary beam or by translating the beam along the length and width directions relative to the stationary substrate. By controlling the rate of the relative scanning of the beam and/or the substrate, the phase transformation of the substrate may be controlled.

[0039] In addition, the particle beam introduced to the substrate may be a focused beam or a non-focused beam. In addition, the particles beam may be uniform or non-uniform along its cross section. For example, a ribbon beam may have a higher current density at its leading edge followed by a trailing edge having a lower current density, or vice versa. The non-uniform beam may have other intensity profiles. It is believed that a non-uniform beam may enhance the nucleation process and the growth process. For example, the non-uniform beam may have an intense leading edge to initiate nucleation, followed by a less intense trailing edge. For example, the high density portion of the beam may initiate the phase transformation by melting the substrate, and the low density portion of the beam may enhance the extent of the transformation by controlling the solidification of the molten region.

[0040] Further, more than one beam may be operated and introduced to the substrate either simultaneously or sequentially. If more than one beam is used the beam may be introduced to the entire width and/or length of the substrate at one time.

Direction

[0041] The particle assisted phase transformation may have some advantage in orienting the crystal growth and/or crystal shapes. In the present disclosure, the particles may be introduced to the substrate at various angles. Introduction of the particles at various angles may be achieved by the tilting the substrate relative to the beam and/or the beam may be tilted relative to the substrate.

[0042] In one embodiment, the particles may be introduced to the substrate at 0° (i.e. perpendicular to the surface of the substrate). The particles introduced at 0° may preferentially destroy {200} grain boundaries that may limit electrical conductivity in FPDs. Alternatively, the particles may be introduced at other angle, for example, 7°.

Substrate Condition

[0043] In addition to the parameters of the particles, the conditions of the substrate may be adjusted before, during, or after introduction of the particles. For example, the temperature of the substrate may be adjusted. In one embodiment, the substrate may be heated to, for example, approximately 500° C. prior to or during the introduction of the particles. Heating the substrate may mitigate thermal shock caused by the particle beam. In addition, heating the substrate may induce formation of larger crystals. For example, heating the substrate may cause the region introduced with the particles to cool at a slower rate (as this region may largely loose its energy through conduction into the substrate).

[0044] The crystallization may be enhanced if the substrate were cooled below room temperature. For example, the substrate may be cooled to a temperature ranging from about 0° C. to about −100° C. In addition, cooling the substrate may prevent the structure of the insulating film from being unstable.

[0045] When the particles are introduced to the substrate, the substrate may be in vacuum or at atmospheric pressure. The vacuum pressure may be higher than those usually associated with ion implantation (i.e. pressure higher than 10-4 mbar) to reduce pump cost.

Exemplary Systems

[0046] Referring to FIG. **3**, there is shown a block diagram of an exemplary system **300** for processing a substrate according to one embodiment of the present disclosure. The system **300** may be a beam-line particle system **300**. The system **300** may comprise an ion source **302**; an extraction system **304**; an acceleration system **306**; optional beam manipulation components **308**; and a neutralization system **310**. In addition, the system **300** may comprise an end station **312** communicating with the neutralization system **310**. The end station **312** may comprise a window **314** and one or more loadlocks **316** and **318**. Within the end station **312**, a platen that supports a substrate **322** may be positioned. In addition, one or more of substrate translation, cooling and/or heating sub-system **324** may be disposed in the end station **312**.

[0047] In the present disclosure, the ion source **302** may be a Bernas type, with indirectly heated cathode. Those of ordinary skill in the art will recognize that the ion source **302** may also be other types of ion source. Meanwhile, the extraction system **304** may be a single slit or, alternatively, a multiple slit extraction system **304**. The extraction system **304** may be translatable in one or more orthogonal directions. In addition, the extraction system **304** may be designed to extract a temporally constant beam current. In addition, the extraction system **304** may extract the particle continuously or intermittently. The extraction system **304** may also focus the particle beam or beamlets to allow a desirable spatial and/or temporal

beam profiles. The particles beam extracted via the extraction system **304** may have energy of approximately 80 keV.

[0048] If higher energy is required, the system **300** may include an acceleration system **306** that may accelerate the particle beam. The system **300** may also include one or more additional, optional beam manipulation components **308** to filter, scan, and shape the particles to a particle beam. As illustrated in FIG. **4**, a specific example of the system **300**, the optional beam manipulation components **308** may include a first magnet analyzer **406**, a first deceleration (D**1**) stage **408**, a second magnet analyzer **410**, and a second deceleration and a second deceleration (D**2**) stage **412**. In the present disclosure, the first magnet analyzer **406**, a substantially dipole magnet, may filter the particles based on the particles' mass and energy such that particles of undesired mass and/or energy will not pass through the magnet analyzer **406**. Meanwhile, the second magnet analyzer **410**, another substantially dipole magnet, may be configured to collimate the particles into a particle beam having desired shape (e.g. ribbon) and/or dimension. D**1** and D**2** deceleration stages **410** and **412** may manipulate the energy of the particles passing through such that the particles may be introduced to the substrate at a desired energy. In one embodiment, the D**1** and/or D**2** may be segmented lenses capable of minimizing the space charge effect and maintaining spatial integrity of the beam.

[0049] Although not shown, the beam manipulation components may also include one or more substantially quadrupole magnets or einzel lenses to focus the beam. Further, the beam manipulation components may also include magnetic multipoles or rods such as described in U.S. Pat. Nos. 6,933,507 and 5,350,926 to control the uniformity of the beam profile.

[0050] Returning to FIG. **3**, the charge neutralization system **310**, according to the present embodiment, may also be included to reduce charge build-up in the substrate **322**. The charge neutralization system **310** may be one or more systems of hot filament, or microwave, or rf driven type, such as that described in U.S. patent application Ser. No. 11/376,850. Alternatively, the charge neutralization system **310** may be an electron source.

[0051] In the end station, the environment around the substrate may be controlled in order to prevent, for example, deposition of other materials on the substrate or to promote passivation to enhance the crystallization process. To control the environment, the end station **312** may include a thin foil window or a differentially pumped aperture **314**, through which the particles may enter, and one or more loadlocks **316** and **318**, through which the substrate may be admitted. The loadlocks **316** and **318** may be replaced by one or more differentially pumped stages through which the substrate may be admitted.

[0052] The end station **312** may also contain substrate movement, cooling, and heating subsystem **324**. Examples of sub-system **324** may include a chiller, a heat source, a roplat capable of translating/rotating the substrate along several axes. Specific examples of the chiller may be found in U.S. patent application Ser. No. 11/504,367, 11/525,878, and 11/733,445, each of which is incorporated by reference in entirety. Specific examples of the heat source may be a laser, flash lamp, platen providing fluid heating, resistive heat source, or those described in U.S. patent application Ser. No. 11/770,220 and 11/778,335, each of which is incorporated by reference in entirety.

[0053] To monitor the process and substrate parameters/conditions, one or more parameters/conditions measuring components may also be included near the substrate **322**. Such components may be coupled to one or more controllers, and the controllers may control the parameters/conditions of the substrate and/or the particles based upon the signals from the measuring components.

[0054] Referring to FIG. **5**, there is shown another exemplary system for processing a substrate according to another embodiment of the present disclosure. In particular, the system **500** may be a PLAD, PIII system, or other plasma based substrate processing system. PLAD system **500** may comprise a chamber **501** including top section **502** and a lower section **504**. The top section **502** may include a first dielectric section **506** that extends in a generally horizontal direction and a second dielectric section **508** that extends in a generally vertical direction. In one embodiment, each dielectric section **506** and **508** may be ceramic that is chemically resistant and that has good thermal properties. The top section **502** may also include at least one or more antennas **510** and **512**. The one or more antennas **510** and **512** may be, for example, a horizontal antenna **510** and/or a vertical antenna **512**. In one embodiment, the horizontal antenna **510** may be a planar coil having multiple windings, whereas the vertical antenna **512** may be a helical coil of multiple windings. At least one of the antennas **510** and **512** may be electrically coupled to a power supply **514** via an impedance matching network **516**.

[0055] On the lower section **504** of the system **500**, a platen **520** and a substrate **522** supported by the platen **520** may be positioned at a predetermined height below the top section **502**. However, it is also contemplated that the platen **502** ad the substrate **522** may be positioned in the top section **502**. A bias voltage power supply **524** may be electrically coupled to the platen **520** to DC or RF bias the platen **520**.

[0056] In operation, at least one of the antennas **510** and **512** may be RF or DC powered by the power source **514**. If only one of the antennas **510** and **512** is RF or DC powered, the other one of the antennas **510** and **512** may be a parasitic antenna. The other one of the antennas **510** and **512** may be a parasitic antenna as it is not electrically coupled to the power source **514**. Instead, the other one of the antennas **510** and **512** is magnetically coupled to the antenna that is powered by the power source **514**. Alternatively, both of the antennas **510** and **512** may be powered by the power source **514** with an RF current. Thereafter, at least one of the antennas **510** and **512** induces the RF currents into the system **500** via the first and second dielectric sections **506** and **508**. The electromagnetic fields induced by the RF currents may covert the gas contained in the system **500** into plasma. Meanwhile, the bias voltage power supply **524** may bias the platen **520** to attract the charged particles in the plasma to the substrate **522**. Additional details of the system 500 may be found in U.S. patent application Ser. No. 11/766,984; application publication No. 2005/0205211; application publication No. 2005/0205212, and application publication No. 2007/0170867, each of which is incorporated in entirety by reference.

Optional Components

[0057] In addition to the components described above, the exemplary systems **300**-**500** may optionally include one or more masks between the particle source (e.g. ion source or plasma) and the substrate. If included, the mask may preferentially be a carbon (C) based material, Si based material (e.g. SiC), or refractory metal, such as W or Ta, containing mate-

rial. However, other materials may also be used. Such a mask may have one or more aperture having various shapes including chevron shape to control the shape of the beam incident on the substrate.

FPD

[0058] Hereinafter, description of several applications of the particle induced phase transformation is provided. As noted above, the particles may be introduced into a Si layer of a thin film substrate to induce the phase transformation from the amorphous to the crystalline phase. For purpose of clarity, a comparison of the particle induced phase transformation is made with the ELA process.

[0059] In the present embodiment, the particles may be directed to an FPD having an amorphous Si film of about 500 Å thick disposed on an insulating film. The insulating film may be, for example, amorphous glass or Corning 1737 glass having a thickness of about 0.7 mm, quartz, plastic, or sapphire. However, those of ordinary skill in the art will recognize that other types of insulating film may also be used.

[0060] In ELA process, a single laser pulse may deliver an energy pulse of 360 mJ/cm^2 in a 12 nanosecond long pulse. This equates to a power density of 3×10^{10} W/m^2. If an Ar ion beam is directed to the Si film, the beam may have an energy of 20 keV. With such energy, all of the directed Ar ions may not penetrate the substrate beyond the Si layer (see FIG. **2**). If a ribbon shaped Ar particle beam is used, the beam may be assumed to have dimensions of 300 mm wide by 0.1 mm tall. With a beam current of 25 mA, this implies a power density of 1.7×10^7 W/m^2.

[0061] In ELA process, the laser beam incident on the substrate may heat the Si layer to 1000° C., near the melting temperature of amorphous Si. Upon incidence, the laser beam may initiate at least a partial melting of Si layer. The thermal diffusivity for Si is relatively high, varying between ~1 cm^2/sec at room temperature and 0.1 cm^2/sec at 1400K. Hence, even if the laser energy is absorbed in the top few nm of the Si surface, absent any latent heat effects, there may be a very small temperature gradient within the Si layer. Heat may diffuse from the Si into the glass. The diffusivity for the glass is small (~0.005 cm2/s over a large temperature range), and so a large thermal gradient may exist across the thick glass layer. The results of the model shown in FIG. **6**, calculate that the glass even within 0.1 μm of the Si, does not reach above 500° C.

[0062] As the particle beam has a lower power density, the exposure time needed to deposit sufficient energy to heat the Si film may be higher (80 ms) compared to the laser (12 ns). In addition, as the heat deposited to the substrate via the particles may be lost to the insulating via thermal conduction, more energy may be needed to heat the Si film sufficiently. Under these assumptions, the insulating film within 50 μm of the Si may be heated above 600° C. Nevertheless, sufficient amount of the insulating may not be heated above its glass transition (or melting) temperature such that these conditions may be acceptable.

[0063] If the height of the ribbon beam were to increase to 1 mm, it may take approximately 2.4 seconds to sufficiently heat the Si film, in which time the peak temperature of the bottom of glass may reach 600° C. This example, compared to the 0.1 mm case in FIG. **7**, demonstrates the need to keep the power density of the beam as high as possible. This may be achieved by maintaining the beam area as small as possible, increasing beam current, and/or increasing the beam energy. The mass of the ion species may also be increased. The use of a molecular particle beam may be desirable as it allows the use of higher beam energies. At the same time, the higher beam energy may reduce additional detrimental effects such as space charge blow-up that may otherwise limit the beam currents and the beam focusing.

[0064] The particle beam irradiation may retain the solid Si in the amorphous phase, allowing melting to occur at 1300K. Crystalline Si does not melt until 1683K. Therefore if the amorphous Si undergoes crystallization before melting commences, more power may be required to completely melt the material. Also, liquid Si may reflect a portion of the laser radiation and so coupling power into the bulk of the Si may be difficult once the Si surface has melted. The presence of a particle beam during the cooling and crystallization phase may influence the production of high quality material.

Thin Film Solar Cell

[0065] The particle induced phase transformation described in the present disclosure may also be applied to manufacture of thin film solar cells. As known in the art, amorphous Si is a direct band gap material and may absorb light more efficiently than crystalline Si, an indirect band gap material. In addition, amorphous Si absorbs more light in the visible spectrum than crystalline Si. However, amorphous Si has lower electrical conductivity. As such, amorphous Si may preferably transform incident radiation to electrical current, whereas crystalline Si may preferably transfer the generated electrical current. Accordingly, the solar cell, according to the present embodiment, may preferably have a layer of amorphous Si above another layer of crystalline Si. Incident radiation at visible wavelengths may be efficiently converted into photocurrent in the amorphous Si. Light not converted in the amorphous layer (including infra-red radiation) may be converted into photocurrent in the crystalline Si.

[0066] Referring to FIG. **8**, there is shown a process that may be incorporated in preparing a substrate according to another embodiment of the present disclosure. In the present embodiment, the substrate may be a thin film solar cell with crystalline and amorphous layers. In another embodiment, the substrate may be a semiconducting layer of a FPD that is disposed on an insulating layer (not shown). As illustrated in FIG. **8**A, an amorphous Si layer **802** may be deposited onto a glass layer (not shown). The Si layer **802** may have thickness of 1.5 μm, whereas the glass layer may have thickness of 3 mm. The particles **804** having a predetermined dose and energy may then be introduced to the amorphous Si layer **802**. As illustrated in FIG. **8**B, the particles **804** may be introduced below the surface of Si layer to crystallize a lower portion of Si layer **802**, without inducing crystallization of the upper portion of amorphous Si layer **802**. The resulting substrate may be used in a solar cell having an amorphous Si layer **802** disposed on the crystal Si layer **806**.

[0067] Referring to FIG. **9**, there is shown a process that may be incorporated in preparing a substrate according to another embodiment of the present disclosure. In the present embodiment, the substrate may be a thin film solar cell with crystalline and amorphous layers. In another embodiment, the substrate may be a semiconducting layer of a FPD that is disposed on an insulating layer (not shown). As illustrated in FIG. **9**A, an amorphous Si layer **902** may be deposited onto a glass layer (not shown). Thereafter, particles **904** having a predetermined dose and energy may be introduced to the amorphous Si layer **902** to crystallize the entire Si layer **906**

(FIG. **9**B). As illustrated in FIG. **9**C, a plurality of particles of second species **908**, energy, and dose may be introduced to the substrate to amorphize a layer near the surface of the crystalline Si layer. The resulting solar cell may have an amorphous top Si layer **904** and a crystalline lower Si layer **902**.

[0068] Referring to FIG. **10**, there is shown a process that may be incorporated in preparing a substrate according to another embodiment of the present disclosure. In the present embodiment, the substrate may be a thin film solar cell with crystalline and amorphous layers. In another embodiment, the substrate may be a semiconducting layer of a FPD that is disposed on an insulating layer (not shown). As illustrated in FIG. **10**A, an amorphous Si layer **1002** may be deposited onto a glass layer (not shown). Thereafter, particles **1004** having a predetermined dose and energy may be introduced to the amorphous Si layer **1002** to crystallize a sub-layer **1006** within the Si layer **1002** (FIG. **10**B). Although FIG. **10**B illustrate a sub-layer disposed near the upper surface of the Si layer **1002**, those of ordinary skill in the art should recognize that the sub-layer **1006** may be positioned near the upper surface, near the lower surface, or anywhere between the upper surface and the lower surface of Si layer **1002**.

[0069] After forming the crystalline sub-layer **1006**, one or more of the crystals in the sub-layer **1006** may be grown away from the sub-layer **1006** until the entire Si layer **1002** may be crystallized. The crystals may be grown via one of furnace annealing, rapid thermal annealing (RTA), flashlamp annealing, and laser annealing. Alternatively, the crystals may be grown by particle assisted annealing. For example, the same or another types of particles (not shown) having another predetermined dose and/or another predetermined energy to the region below the crystallized sub-layer to extend the grain boundary of one or more crystals toward the lower surface of the substrate. In the process, the entire Si layer **1002** may contain one or more crystals having grain boundaries that extend in a vertical direction. The present embodiment may also include an optional amorphizing step to amorphize a portion of the newly crystallized Si layer **1006**. For example, the particles **1010** may then be introduced to the newly crystallized Si layer **1002** to amorphize at least a portion of the newly crystallized Si layer **1002** (FIG. **10**D) to form an amorphous sub-layer **1012**. In the present disclosure, the particles introduced to the newly crystallize Si layer **1002** the same particles as those used to crystallize the previous amorphous Si layer **1002**. Alternatively, the particles introduced to the newly crystallize Si layer **1002** may be different from those used to crystallize the previous amorphous Si layer **1002**. The above process may be used to crystallize a thick amorphous Si layer.

[0070] The particle induced phase transformation may also be used to manufacture an efficient polycrystalline Si solar cell. The grain boundaries of crystals may be efficient sites for gettering impurities, such as metal contaminants. In addition, grain boundary may serve as a barrier for charge carriers' mobility, inhibiting the carriers from traveling through the boundary. Accordingly, polycrystalline solar cells having multiple crystals, thus multiple grain boundaries, may have relatively low electrical conductivity if the grain boundaries are located across the path of the charge carriers. In the polycrystalline solar cells, electrical current generated at the upper surface must be transported to contact areas, which are generally located at the lower surface of the solar cell. If the grain boundaries in the polycrystalline solar cells are positioned across the path of the charge carriers, the efficiency of the solar cells may be lowered. As such, it may be desirable to manufacture polycrystalline solar cells having grain boundaries oriented in parallel manner relative to the path of the charge carriers.

[0071] To manufacture an efficient polycrystalline solar cell, an amorphous Si substrate may be prepared. Thereafter, the upper surface of the Si layer may be crystallized, and the crystals may grow downward per solid phase epitaxial regrowth (SPER). The ion energy may be chosen so that the power density delivered to the substrate may be maximized. This may correspond to an energy of between 40 to 100 kev, where typical ion beam systems can extract the maximum beam currents from an ion source and where space charge effects are reduced for beam transport and focusing. Such an ion beam may cause crystallization near the surface of the silicon which in turn may seed SPER downwards until the whole layer is crystallized. The SPER may take place as part of the beam induced crystallization step, or in a further annealing step that may use one or more of furnace, RTA, flashlamp, laser or other annealing methods. The resulting substrate will likely to have crystals with vertically extending grain boundaries. Thereafter, particles of second species, energy, and dose may be introduced to the substrate to amorphize a layer near the surface of the polycrystalline substrate. The solar cell may then have a structure of amorphous Si layer above vertically extending polycrystalline Si layer. As noted above, such a solar cell will likely to convert radiation energy to electrical energy more efficiently, and, at the same time, transport the converted electrical energy more efficiently.

[0072] In the present disclosure, the size and orientation of the boundaries may be influenced by the choice of the particle beam conditions used to assist the crystallization of the top layer. Phosphorous may be a favorable species as it is a good getter species, and may be the dopant of choice for the solar cell. The direction of implant may be chosen to influence the grain orientation. The whole active layer may be implanted, or the surface layer may be implanted to create a top crystalline surface with few voids, and the rest of the substrate may be regrown by SPER.

[0073] The terms and expressions which have been employed herein are used as terms of description and not of limitation, and there is no intention, in the use of such terms and expressions, of excluding any equivalents of the features shown and described (or portions thereof), and it is recognized that various modifications are possible within the scope of the claims. Other modifications, variations, and alternatives are also possible. Accordingly, the foregoing description is by way of example only and is not intended as limiting. What is claimed is any feature detailed herein.

1-19. (canceled)

20. A method for processing a substrate, the method comprising:

generating a continuous particle beam containing a plurality of particles; and

introducing the continuous particle beam to a region of the substrate in an amorphous phase and transforming the region from the amorphous phase to a crystalline phase, wherein the continuous particle beam has a current density of 5×10^{14} particles/cm^2 sec or greater.

21. The method of claim **20**, wherein the continuous particle beam is a focused particle beam.

22. The method of claim **20**, wherein the continuous particle beam has decreasing density profile from a first cross sectional end to a second cross sectional end of the beam.

23. The method of claim **22**, wherein the first cross sectional end is a leading end and the second cross sectional end is a trailing end following the leading end, the leading end introduced to the region prior to the trailing end.

24. The method of claim **20**, further comprising:

adjusting energy of the continuous particle beam during the introducing the continuous particle beam to the region of the substrate.

25. The method of claim **24**, wherein the adjusting comprises adjusting the energy of the continuous particle beam linearly.

26. The method of claim **24**, wherein the adjusting comprises adjusting the energy of the continuous particle beam in sequence.

27. The method of claim **20**, further comprising:

melting at least a portion of the region prior to transforming the first region from the amorphous phase to the crystalline phase.

28. The method of claim **20**, further comprising:

transforming the first region from the amorphous phase to the crystalline phase without melting at least a portion of the region.

29. The method of claim **20**, wherein the particles comprises molecular ions.

30. The method of claim **20**, wherein the particles comprises cluster particles.

31. The method of claim **20**, wherein the particles comprises protons or deuterons.

32. The method of claim **20**, wherein the particles comprises one or more species chosen from a group consisting of: He, Ne, Ar, Kr, Xe, and Rn.

33. The method of claim **20**, wherein species of the particles is Ga.

34. The method of claim **20**, wherein the region comprises Si and wherein the particles comprises one or more species chosen from a group consisting of C and Ge, so as to convert the region introduced with the continuous particle beam to a stressed region.

35. The method of claim **20**, wherein the region comprises a material selected from Group IV elements and wherein the particles comprises one or more species chosen from a group consisting of B, Ga, In, P, As, Sb, and Bi, so as to change an electrical property of the region.

36. The method of claim **20**, wherein the region comprises a material selected from Group IV elements and wherein the particles comprises one or more species chosen from a group consisting of Yb, Ti, Zr, Hf, Pd, Pt, and Al, so as to change a bandgap property of the region.

37. The method of claim **20**, wherein the region comprises a material selected from Group IV elements and wherein the particles comprises one or more species chosen from a group consisting of C containing particles, Si containing particles, Ge containing particles, F containing particles, N containing particles, H containing particles, He containing particles, Sn containing particles, and Pb containing particles, so as to prevent changing of an electrical property of the region.

38. The method of claim **20**, wherein the region comprises a material selected from Group IV elements and wherein the particles comprises metallic particles so as to increase a rate of the transformation of the region from the amorphous phase to the crystalline phase.

39. The method of claim **38**, the metallic particles comprises Ni particles.

40. The method of claim **20**, further comprising:

changing temperature of the substrate prior to introducing the continuous particle beam to the region of the substrate.

41. The method of claim **40**, wherein the changing the temperature comprises decreasing the temperature.

42. The method of claim **20**, further comprising:

disposing a mask comprising at least one aperture between the substrate and an ion source that generate the plurality of particles, to introduce the particles to a portion of the region of the substrate.

43. The method of claim **20**, wherein the introducing the continuous particle beam to the region comprises periodically changing relative positions of the substrate and the beam so as to intermittently prevent the beam from reaching the region.

44. The method of claim **43**, wherein the periodically changing the relative positions of the substrate and the beam is achieved by changing the position of the beam relative to a stationary substrate.

45. The method of claim **20**, wherein the periodically changing the relative positions of the substrate and the beam is achieved by changing the position of substrate relative to a stationary beam.

46. The method of claim **20**, wherein the continuous particle beam is introduced to the region at an angle perpendicular to the upper surface of the substrate.

47. The method of claim **20**, wherein the continuous particle beam is introduced to the region at an angle other than an angle perpendicular to the upper surface of the substrate.

48. The method of claim **20**, further comprising:

preventing the plurality of particles of the continuous particle beam from traveling to a portion of the substrate outside of the region.

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