

**APPLICATION SPECIFIC IMPLANT SYSTEM AND METHOD  
FOR USE IN SOLAR CELL FABRICATIONS**

**Related Application**

5           This application claims priority under 35 U.S.C. § 119(e) to the co-pending U.S. Provisional Application Serial Number 61/131,687, filed June 11, 2008, entitled "SOLAR CELL FABRICATION USING IMPLANTATION," co-pending U.S. Provisional Application Serial Number 61/131,688, filed June 11, 2008, entitled "APPLICATIONS SPECIFIC IMPLANT SYSTEM FOR USE IN SOLAR CELL FABRICATIONS," co-  
10    pending U.S. Provisional Application Serial Number 61/131,698, filed June 11, 2008, entitled "FORMATION OF SOLAR CELL- SELECTIVE EMITTER USING IMPLANTATION AND ANNEAL METHODS," and co-pending U.S. Provisional Application Serial Number 61/133,028, filed June 24, 2008, entitled "SOLAR CELL FABRICATION WITH FACETING AND IMPLANTATION," co-pending U.S. Provisional  
15    Application Serial Number 61/210,545, filed March 20, 2009, entitled "ADVANCED HIGH EFFICIENCY CRYSTALLINE SOLAR CELL FABRICATIONS METHOD," which are all hereby incorporated by reference as if set forth herein.

**Field of the Invention**

20           This invention relates to the manufacture of semiconductor devices. More specifically, this invention relates to systems for and methods of fabricating solar cells.

**Background of the Invention**

25           Semiconductor devices are manufactured using multi-purpose semiconductor fabrication tools. Because of the ever-decreasing dimensions of current semiconductor devices, these tools fabricate devices according to strict specifications. Being multi-purpose, these tools generate ions of different species for different fabrication steps, using beams that span a wide range of energies. Capable of fabricating small-geometry devices, these tools have strict scanning dimensions. They also perform mass analyses to reduce contamination  
30    and include a special module to neutralize the collected charge on a substrate. Because these tools are so complex and their requirements are so stringent, their output is relatively small, only about 200 wafers per hour.

          Figure 1 show a prior art implant system 100 for implanting substrates as one step in fabricating a semiconductor device. Multiple wafers are introduced into the system 100  
35    through twin load locks 105. A multiple gas delivery module 110 contains multiple gases

from which n-type and p-type ions (dopants) are extracted. The ions are accelerated by a pre-accelerator 120, which transmits them to a magnet 125 that performs mass analysis to reduce contamination. The ions are then transmitted to a post-accelerator 130 and then on to a charge neutralization module 135. The beam of ions is scanned across the surfaces of multiple wafers 101 using a beam scanning mechanism 140; alternatively, the wafers 101 themselves are moved relative to the beam. A Measurements and Control unit 145 then analyzes the wafers 101.

Because the system 100 must be able to implant different dopants, the operating range of the pre-accelerator 120 and the magnet 125 must be large, generally less than 10 keV to 200 keV—sufficient to implant all the dopant types. The system 100 must also be capable of satisfying the stringent requirements of advanced geometries (smaller than 65 nm). As one example, uniformity requirements of less than 0.5% require multiple beam scans, which reduces system productivity.

A second drawback is that features on the devices vary during different stages of device fabrication. These features cannot withstand the high temperatures or collected charge to which they are exposed. Furthermore, the features themselves can adversely affect the implant beam, such as when an insulating film collects charge during its formation.

With few exceptions, device fabrication requires beams with large power densities and the generation of high temperatures. These limitations in general make prior art fabrication systems complex.

## Summary of the Invention

In a first aspect, a system for implanting a semiconductor substrate includes an ion source, an accelerator to generate from the ion source a beam having an energy no more than 150 keV, and a beam director to expose the substrate to the beam. In one embodiment, the ion source includes a single-species delivery module that includes a single-gas delivery element and a single-ion source. The beam director includes a focusing element, such as electrostatic and electromagnetic optics, used to focus or shape the beam onto the substrate. In another embodiment, the ion source includes a plasma source (such as a single-ion plasma source) that generates the ions that are extracted. This other embodiment also includes an accelerator and a beam director that spreads the ions to encompass or otherwise fully cover the substrate.

In one embodiment, the single-ion plasma source has a beam slot length of between 5 and 10 cm and a width of less than 5 mm. Alternatively, the single-ion plasma source has a broader slot length, width, or both. Additionally, a magnetron generated plasma source can

be used to generate a very large plasma that the substrate can be immersed within for implantation. The ion source contains an n-type dopant, such as antimony, arsenic, or phosphorous. Of course, other n-type dopants can also be used. Alternatively, the ion source contains a p-type dopant, such as boron, aluminum, gallium, indium, or  $\text{BF}_2$ . Other p-type dopants can also be used.

The beam has a power density of about 5 kW per square centimeter. In one embodiment, the single-ion source is plug-compatible with the system, such as with the single-species delivery module.

In one embodiment, the beam director includes a scanning element to step the beam across the substrate in orthogonal directions.

In a second aspect, a method of fabricating a semiconductor device includes forming photo-receptive regions within a substrate, doping the photo-receptive regions to form gridlines, and coupling metal fingers to the gridlines. The photo-receptive regions are doped with a dopant at a first concentration and with the dopant at a second concentration larger than the first to form the gridlines. The gridlines extend from topmost surfaces of the photo-receptive regions down into the substrate. The photo-receptive regions are doped and the gridlines are formed using a system that includes a single-species delivery module. Metal fingers are coupled to the gridlines. Thus, the substrate has photo-receptive regions of low dopant distribution and of high dopant distribution underneath the metal fingers.

In one embodiment, the substrate is doped singly, separately from other substrates. In another embodiment, the substrate is doped in a group, with other substrates.

In one embodiment, the gridlines are formed by exposing the substrate through a mask to an ion beam containing the dopant. The mask is displaced from a surface of the substrate and has openings sized to widths of the gridlines. Alternatively, the widths are at a known deviation from the widths of the gridlines. In another embodiment, the mask is placed on a surface of the substrate and has openings adjacent to the locations where the gridlines are to be formed. In still another embodiment, the gridlines are formed by shaping or pulsing a plasma beam containing the dopant to a width of the gridlines and directing the beam onto the photo-receptive regions. In this latter embodiment, the plasma beam is stationary. In another embodiment, the ion beam is scanned across the photo-receptive regions to sequentially form the gridlines, or it is generated to form the gridlines simultaneously.

In one embodiment, the first concentration (dose) is less than  $1E15$  per square centimeter. The photo-receptive regions have a resistance of approximately 100 ohms per square. The gridlines have a resistance of about 10 to 30 ohms per square, are no more than 200 microns wide, and are no more than 5 millimeters apart. In one embodiment, the gridlines are about 3 millimeters apart.

The method further includes implanting a metal seed on each of the gridlines before coupling them to metal fingers, thus forming a metal silicide.

In one embodiment, the method also includes annealing the substrate, such as by using a furnace, a flash lamp, or a laser. The substrate can be annealed in a single step at low temperatures, such as between 400 and 500 °C.

In a third aspect, a method of fabricating a solar cell includes doping photo-receptive regions within a substrate to a first concentration using an ion beam having an energy of no more than 150 kV, doping the photo-receptive regions to a second concentration larger than the first concentration using the ion beam to form gridlines, and coupling metal fingers to the gridlines. The gridlines extend from topmost surfaces of the photo-receptive regions down into the substrate. The substrate is 156 mm x 156 mm, the photo-receptive regions are doped using a system that includes a single-species delivery module. The system has a throughput of at least 1,000 wafers per hour.

## **Brief Description of the Drawings**

Figure 1 shows a prior art semiconductor device fabrication system.

Figure 2 shows a semiconductor device fabrication system according to the embodiments.

Figures 3A and 3B show beam optics for shaping beams in accordance with the embodiments.

Figure 4 shows a lightly doped photo-receptive region of a solar cell in accordance with one embodiment.

Figures 5A-C show forming gridlines by doping the photo-receptive region of Figure 4 in accordance with different embodiments.

Figure 6 shows using seeds to couple the gridlines to metal fingers of the solar cell of Figure 4 in accordance with one embodiment.

Figure 7 is a profile tailoring graph in accordance with one embodiment.

Figure 8 is a graph illustrating the deficiencies in profile tailoring ability for solar cells that are doped using diffusion.

Figures 9A and B are graphs illustrating the advantages in profile tailoring ability for solar cells that are doped using ion implantation in accordance with one embodiment.

Figure 10 shows the steps of a process for fabricating a solar cell in accordance with one embodiment.

5

### Detailed Description of the Invention

Systems in accordance with the invention are specifically tailored to fabricate specific semiconductor devices, such as solar cells. These systems use tolerances that are more relaxed than those required to fabricate other semiconductor devices. They fabricate devices more quickly, less expensively, and in a smaller space than do prior art systems. Such systems are capable of producing at least 1,000 solar cells per hour.

Systems are further simplified because no charge neutralization is used since wafers have no featured coverings, scanning is simplified, and mass analyses can be performed using other methods. All of these advantages result in an output higher than can be realized using traditional semiconductor fabrication systems.

Systems in accordance with the embodiments also produce more efficient solar cells, solar cells with doping profiles tailored to reduce ohmic losses and the effects of dead layers.

Figure 2 shows a system 200 for fabricating solar cells in accordance with one embodiment. The system 200 is simpler than the prior art system of Figure 1: It has a higher productivity, has a smaller footprint, and has plug-compatible components (which can be swapped out and replaced with other species-specific modules). The system 200 includes a single-gas delivery module 205, an ion source 210, an accelerator 215, a skewed Beam Scanning, Mass Analysis, and Beam Shaping module 220, a Measurement and Control module 225, and a single load lock 230 to handle a single solar cell 201. In another embodiment (not shown), the single-gas delivery module 205 and ion source 210 are replaced with a plasma source module, and the Beam Shaping module 220 is replaced with a spreader for spreading a plasma beam onto the solar cell 201.

The system 200 has specific capabilities. It will be appreciated that not all embodiments have these capabilities. The ion source 210 has a long slot. In alternative embodiments, the ion source 210 includes multiple ion sources for the formation of broad and narrow, or plasma beams. The ion source 210 produces beam currents up to 100 mA of all species but is dedicated to a single species at one time. The ion source 210 is also plug-compatible for each specific application: when a new application with a different ion beam source is required, the ion source 210 can be pulled out and replaced with a different one that meets requirements (e.g., different dopant) of the next application. The ion source 210 has a

beam slot of less than 5 to 10 cm and a width of 1 to 2 mm. Alternatively, the ion source 210 is a plasma source and can be configured to produce a broad beam. The length can be stretched to cover one dimension of a 156 mm x 156 mm substrate or both dimensions of the substrate.

5 In operation, the single-gas delivery module 205 and ion source 210 together generate an ion beam, which is accelerated by the accelerator 215, either in DC fashion or pulsed. In one embodiment (Figure 3), the accelerator has extraction and focusing elements with a limited energy range, such as between 15 and 150 keV. In other embodiments, other limited energy ranges are used. Preferably, to limit the energy requirements of the system 200, the  
10 accelerator 215 does not operate above 100 keV.

Next, the resulting skewed beam is controlled using the Beam Scanning, Mass Analyzing, and Shaping module 220. The beam is further measured and controlled using the Measurement and Control module 225 before or at the same time as the beam impinges on a single wafer 201. The single wafer 201 can be stepped in front of the beam to implant  
15 dopants according to a predetermined pattern, using a single beam to cover the entire surface of the wafer 201. In one embodiment, the wafer 201 is 156 mm x 156 mm, but the system 200 is capable of processing wafers of other dimensions. In alternative embodiments, a wafer is deployed before the beam on a moving platen, or one or more wafers on a tray are exposed to the beam.

20 Finally, the processed single wafer 201 is removed from the system 200 through the single load lock 230.

Figures 3A and 3B are beam shapers 300 and 350 (also referred to as “beam optics”) in accordance with two embodiments for shaping beam spots to implant dopants into a substrate 401. In one embodiment, the beam shapers 300 and 350 form part of the Beam  
25 Shaping module 220 of Figure 2. The beam shapers 300 and 350 each comprises a magnetic or electrostatic lens. As discussed in more detail below, the shapers 300 and 350 can be used to implant selective emitters in semiconductor solar cells.

The beam shaper 300 is a “large dimension” shaper. The beam shaper 300 receives a beam 301A having a first width and shapes it to produce a beam 301B having a second  
30 width, larger than the first, of about 5 to 10 cm, up to the dimensions of the substrate and its holder. Alternatively, the second width is about 15.6 cm.

The beam shaper 350 is a “short dimension” shaper. The beam shaper 350 receives a beam 351A having a first width and shapes it to produce a beam 351B having a second  
35 width, smaller than the first, of about 200 microns. Alternatively, the second width is about 50 microns.

The beam shapers 300 and 350 are also able to eliminate unwanted impurities entrained within a beam. For example, a slight change in the scanning angle can eliminate unwanted neutral particles or species with different charge-to-mass ratios. Alternatively, the internal cladding inside of the chamber containing the beam can be made to minimize the side wall contamination, in particular when the beam is a plasma beam.

Using the beam shapers 300 and 350, the Beam Scanning, Mass Analyzing, and Shaping module 220 (Figure 2) is able to “shape” beams to implant semiconductors of varying geometries.

Preferably, the beam spot dimension, beam currents, and scanning methods have a beam power density of 5 kW/cm<sup>2</sup> and do not raise the average temperature of the wafer 201 (Figure 2) more than 150 °C in its bulk. The wafer 201 is cooled using back side cooling, elastomeric methods, or electrical cooling methods.

Beam-limited pulse-shaping methods can also be used to cool a wafer. Using these methods, the temperature of a wafer is limited by sharing a beam between any other single wafers, within one or more batches of wafers, all using automated controls. Alternatively, the system can use a pulse plasma source to distribute the heat over time rather than position.

As explained above, embodiments of the invention are well suited for fabricating semiconductor solar cells. The following co-pending patent applications, each of which is incorporated by reference in its entirety, describe different ways of fabricating solar cells:

U.S. Application Serial No. XX/XXX,XXX, filed June 11, 2009, titled “Solar Cell Fabrication Using Implantation,” by Babak Adibi and Edward S. Murrer, and having Attorney Docket No. SITI-00100; U.S. Application Serial No. XX/XXX,XXX, filed June 11, 2009, titled, “Formation of Solar Cell-Selective Emitter Using Implant and Anneal Method,” by Babak Adibi and Edward S. Murrer, and having Attorney Docket No. SITI-00300; and U.S. Application Serial No. XX/XXX,XXX, filed June 11, 2009, titled “Solar Cell Fabrication with Faceting and Ion Implantation,” by Babak Adibi and Edward S. Murrer, and having Attorney Docket No. SITI-00400. Figures 4, 5A-C and 6 illustrate using the system 200 (Figure 2) to fabricate a solar cell in accordance with the embodiments.

Solar cells function by receiving light energy on a lightly doped photo-receptive surface that overlies a doped semiconductor substrate, producing electron-hole pairs. The electrons in these pairs form currents that travel along the layer in the substrate, on to a heavily doped selective emitter that draws them to gridlines, to metallic fingers and busbars, and ultimately to a load. These electrons then travel back to the bulk of the substrate, where they recombine with the separated holes.

Generally, the photo-receptive regions are doped in the same step and thus to the same concentration as the area under the gridlines. For such doping, the use of these diffusion methods creates a heavy excess of un-activated dopant species very near the surface of the substrate. This results in a "dead layer": Because the photo-receptive regions need to be lightly doped but have an excess of un-activated dopants, captivated electrons are formed when light strikes the solar cell and recombine with un-paired holes before generating any current. This effect reduces the efficiency of the solar cell.

The dead layer can be reduced by better control of un-activated dopants near the surface region of the substrate. The embodiments shown in Figures 4 and 5A-C show how the selective emitter can be formed by doping the photo-receptive regions to a concentration larger than that in between the gridlines.

Figure 4 is a side-cross-sectional view of a substrate 500 to be formed into a solar cell and having a lightly doped photo-receptive region 505. In this example, the substrate 500 is a p-type semiconductor substrate and the region 505 is doped with n-type ions at a first concentration. The region 505 has a resistance of about 100 ohms per square; excess dopants impede the generation and transport of the dopant charge carriers. The region 505 is typically implanted with an energy implant of less than about 50-100 keV at a concentration of less than  $1E15/cm^2$ . Some examples of n-type dopants are antimony, arsenic, and phosphorous.

In accordance with the embodiments, the substrate 500 is doped using a beam that is broadened to provide whole coverage or is scanned rapidly (element 220, Figure 2) in the x-direction, the y-direction, or both to cover the entire substrate 500. For solar cells, non-uniformity of coverage is estimated at less than 5% (e.g., uniformity of coverage at more than 95%), thus requiring similar homogeneity in the beam spot profile. The beam shapers 300 and 350, shown in Figures 3A and 3B, allow for high productivity implantation.

Figures 5A-C show alternative ways to dope the substrate 500 with an n-type dopant, at a higher concentration than the lightly doped region 505, to form the gridlines 580A-C, thus reducing the formation of a dead layer. In the embodiment shown in Figure 5A, a physical mask 515 is positioned above the photo-receptive regions 505. The mask 515 has openings shaped to the dimensions of the desired gridlines 580A; alternatively, the openings are slightly larger than the dimensions of the gridlines 580A, by a known amount. An ion beam 600 is then directed onto the mask 515 to thereby form the gridlines 580A. In alternative embodiments, the beam 600 is a plasma beam, to which the substrate 500 is exposed. This arrangement can be used in combination with beam scanning or beam shaping methods, such as described above, to maximize the beam utilization.

In the embodiment shown in Figure 5B, a mask 550 is placed on the photo-receptive regions 505. The mask 550 can be hard or soft, and can be formed using lithography, contact printing, or screen printing. Alternatively, an already existing mask used for contact deposition can also be used. Again, an ion beam 610 is directed onto the mask to thereby  
5 implant the gridlines 580B. In alternative embodiments, a plasma beam is used instead of the ion beam 610.

In the embodiment shown in Figure 5C, an implant beam 620 is shaped to dope the substrate 500 and thus form the gridlines 580C. This arrangement can use a series of beam  
10 lets for simultaneous exposure, using a single scanning and stepping beam spot that scribes across the substrate 500. Alternatively, a broad and narrow beam can be used to individually expose one or any number of the gridlines 580C.

Figure 6 shows the substrate 500 after later processing steps, in which the work function and band gap are adjusted by the formation of a metal/semiconductor region. As shown in Figure 6, a metallic species 700 is implanted on regions below the contact fingers,  
15 on top of the gridlines 580 (any one of 580A-C), and also on a back surface of the substrate 500 (not shown). Such "seed" implants increase the contact performance to the metallic fingers (attached to the gridlines) and to the load.

Referring to Figure 6, the doping between adjacent gridlines 580 is approximately 100 ohms per square, the doping under the gridlines 580 is less than 10-30 ohms per square,  
20 the distance X between grid lines is about 3 mm and is expected to be reduced to 1 mm, and the width Y of the metallic species (the metallic fingers) is about 200 microns and is expected to be reduced to 50 microns.

The substrate 500 can be grown single or mono-crystalline, poly-crystalline, or multi-crystalline silicon, thin-film deposited silicon, or any other materials used to form solar cells.  
25 It will be appreciated that other types of substrates and dopings can be used. As only one example, the substrate 500 can be n-type and the gridline 580A can be p-type. Examples of p-type dopants include boron and boron difluoride. Those skilled in the art will recognize many other combinations of semiconductor types, ions, doping levels, and other characteristics.

Figures 7, 8, 9A, and 9B are all used to illustrate how systems in accordance with the  
30 embodiments (e.g., the system 200 in Figure 2) tailor doping profiles to reduce the formation of dead layers and ohmic losses.

Figure 7 illustrates one embodiment of a profile tailoring graph 800 in accordance with the principles of the present invention. The graph 800 represents the atomic profile of a  
35 solar cell with respect to dopant concentration ( $\text{At./cm}^3$ ) versus its dopant depth (Ang.). The

total atomic profile is represented by line 810. Through the use of multiple ion implants, each having a different concentration-versus-depth profile, the dopant concentration (and thus the resistivity) of the solar cell can be precisely adjusted and controlled across predetermined depths by the user. Graph 800 shows three different implantation profiles 812, 814, and 816. The combination of these three profiles results in the total profile 810 of the solar cell.

Although each individual implantation can be limited to a Gaussian or pseudo-Gaussian distribution, the present invention combines them to effectively tailor the shape of the total atomic profile. In controlling the total atomic profile through the use of multiple independent implants, the present invention enables the user to effectively control the junction depth 840, where the implanted dopant of one type (such as n-type dopant) meets the dopant of the pre-doped background region 820 (such as p-type dopant). The user is also enabled to also control the dopant concentration 830 at or near the surface of the solar cell. The present invention allows the user to control the surface concentration 830 and the junction depth 840 independently of one another. In some embodiments, the atomic profile is tailored to have the junction depth in the range of approximately 0.01 micrometers to approximately 0.5 micrometers. In some embodiments, the atomic profile is tailored to have the surface concentration in the range of approximately  $5 \times 10^{18}$  At./cm<sup>3</sup> to approximately  $4.8 \times 10^{21}$  At./cm<sup>3</sup>. However, it is contemplated that the atomic profile can be tailored to have different junction depths and surface concentrations.

In the prior art, the adjustment of the atomic profile is limited. Figure 8 is a graph 900 illustrating the deficiencies in profile tailoring ability for solar cells that are doped using diffusion. Here, line 910 represents an atomic profile for a solar cell. The use of diffusion to dope the semiconducting wafer prevents the user from being able to independently control the surface concentration and the junction depth. The user is limited to either making the profile 910 deeper by simply increasing the concentration and depth together to line 910' or making the profile 910 shallower by decreasing the concentration and depth together to line 910". The user is not able to change the shape of the atomic profile and affect one aspect of the atomic profile more than the other.

Figures 9A-B are graphs illustrating the advantages in profile tailoring ability for solar cells that are doped using ion implantation in accordance with the principles of the present invention. In graph 1000 of Figure 9A, the atomic profile 1010 in terms of concentration-versus-depth is illustrated for a solar cell formed using prior art methods. Here, the profile 1010 is limited to a simple Gaussian distribution, making it difficult for the electrons generated in the electron-hole pair generating region to travel up to the contacts.

The steep slope of the profile 1010 reflects the significant increase in dopant concentration (and thus resistivity) as the electrons travel towards conductive contacts at the surface of the wafer. This steep slope can make it more difficult for the electrons to reach the contacts, thus resulting in an undesirable loss of electricity.

5           In graph 1000' of Figure 9B, the atomic profile 1010' in terms of concentration-versus-depth is illustrated for a solar cell formed using the multiple ion implants of the present invention. The profile 1010' can be shaped to form a more gradual (less steep) increase in concentration as the electrons travel towards the contacts at the surface of the semiconducting wafer. This tailoring of the atomic profile is made possible by the use of  
10 multiple ion implants to independently control the junction depth and the surface concentration, as well as everything in between.

          In Figure 7, the different implantations 812, 814, and 816 can determine different aspects of the solar cell. For example, in some embodiments, line 812 (the mid-range implant) determines the homogeneous emitter, while lines 814 and 816 are added as a series  
15 of selective implants to provide the selective emitter region. These implantation steps can be performed either on blanket substrates, without any covering, or through any anti-reflective covering (e.g., nitride, oxide or any other films), as well as on surface texturing that is required for solar cell fabrications. In the case of texturing, ion implantation provides a good adherence to the surface contour, and thus improves the contact formation. Texturing is  
20 described in U.S. provisional application no. 61/133,028, which is incorporated by reference above. Graph 800 of Figure 7 shows surface coating 850, such as the anti-reflective coating previously discussed. This coating can be any thickness.

          Figure 10 is a flow chart showing the steps of a process 1100 for fabricating a solar cell in accordance with the embodiments. Referring to Figures 2 and 10, the process starts in  
25 the step 1101 in which, for example, a specific ion source 210 required to fit the processing application is plugged into the system 200. In the step 1103, a single wafer is placed into the load lock 230. In the step 1105, the wafer is processed by doping photo-receptive regions at one concentration and at a higher concentration to form the gridlines. This step can include multiple doping cycles.

30           Next, in the step 1107, contact seeds, printed or inkjet printed metallic fingers, busbars and other contacts are formed. In the step 1109, the wafer is fired to establish the contacts and activate and anneal the substrate dopings. The wafer can be annealed using a

furnace, flash lamp or laser, to name only a few devices, at temperatures between 400 and 500 degrees centigrade, temperatures lower than those required using prior art systems. Preferably, only a single annealing step is required. The wafer can also be annealed at different temperatures for a time that brings about comparable results.

5           In the step 1111, the wafer is measured for performance and then sorted. The process ends in the step 1113.

          Preferably, the steps 1100 are performed by a controller using (1) computer-executable instructions stored on a computer-readable medium and (2) a processor that executes the instructions. Referring to Figure 2, in one embodiment this controller (not  
10       shown) is operatively coupled to the Beam Scanning, Mass Analysis and Beam Shaping module 220, the Measurement and Control module 225, or both.

          Though the embodiments describe solar cells, it will be appreciated that other semiconductor devices can be fabricated in accordance with the embodiments.

          It will be readily apparent to one skilled in the art that other modifications may be  
15       made to the embodiments without departing from the spirit and scope of the invention as defined by the appended claims.

**Claims**

What is claimed is:

- 5        1.        A system for implanting a semiconductor substrate comprising:  
             an ion source;  
             an accelerator to generate from the ion source a beam having an energy of no more  
             than 150 kV; and  
             a beam director to expose the substrate to the beam.
- 10       2.        The system of claim 1, wherein the ion source is a single-species delivery module  
             comprising a single-gas delivery element and a single-ion source.
- 15       3.        The system of claim 2, wherein the beam director comprises a focusing element,  
             wherein the focusing element comprises magnetic optics, electromagnetic optics, or  
             both to focus the beam onto the substrate.
- 20       4.        The system of claim 2, wherein the single-ion source has a beam slot length of  
             between 5 and 10 cm and a width of less than 5 mm.
- 25       5.        The system of claim 1, wherein the beam is a plasma beam.
6.        The system of claim 1, wherein the ion source contains an n-type dopant selected  
             from the group consisting of antimony, arsenic, and phosphorous.
- 30       7.        The system of claim 1, wherein the ion source contains a p-type dopant.
8.        The system of claim 1, wherein the beam has a power density of at least 5 kW per  
             square centimeter.
9.        The system of claim 1, wherein the ion source, the accelerator, or both are plug-  
             compatible with the system.
- 35       10.       The system of claim 1, further comprising a scanning element to step the beam across  
             the substrate in orthogonal directions.

11. A method of fabricating a semiconductor device comprising:  
doping photo-receptive regions within a substrate to a first concentration;  
doping the photo-receptive regions to a second concentration larger than the first  
concentration to form gridlines, wherein the gridlines extend from topmost surfaces  
of the photo-receptive regions down into the substrate; and  
coupling metal fingers to the gridlines,  
wherein the photo-receptive regions and the gridlines are doped using a system  
comprising a single-species delivery module.
12. The method of claim 11, wherein the substrate is doped separately from other  
substrates.
13. The method of claim 11, wherein forming the gridlines comprises exposing the  
substrate through a mask displaced from a surface of the substrate to an ion beam  
containing a dopant, wherein the mask has openings sized to widths of the gridlines.
14. The method of claim 11, wherein forming the gridlines comprises exposing the  
substrate through a mask coupled to a surface of the substrate to an ion beam  
containing a dopant, wherein the mask has openings adjacent to where the gridlines  
are to be formed.
15. The method of claim 11, wherein forming the gridlines comprises shaping a beam  
containing dopants to a width of the gridlines and directing the beam onto the photo-  
receptive regions.
16. The method of claim 15, wherein directing the beam comprises scanning the beam  
across the photo-receptive regions to sequentially form the gridlines.
17. The method of claim 15, wherein directing the beam comprises generating the beam  
to simultaneously form the gridlines.
18. The method of claim 11, wherein the first concentration is less than  $1\text{E}15$  per square  
centimeter.

19. The method of claim 11, wherein the photo-receptive regions have a resistance of at least 100 ohms per square.
20. The method of claim 11, wherein the gridlines have a resistance of about 10 to 30 ohms per square.
21. The method of claim 11, wherein the gridlines are no more than 200 microns wide.
22. The method of claim 11, wherein the gridlines are no more than 5 millimeters apart.
23. The method of claim 11, further comprising annealing the substrate at between 400 and 500 degrees Centigrade.
24. The method of claim 11, further comprising forming a contact on a back surface of the substrate.
25. The method of claim 11, further comprising implanting a seed on each of the gridlines before coupling the gridlines to metallic fingers.
26. A method of fabricating a solar cell comprising:  
doping photo-receptive regions within a substrate to a first concentration using an ion beam having an energy of no more than 150 kV;  
doping the photo-receptive regions to a second concentration larger than the first concentration using the ion beam to form gridlines, wherein the gridlines extend from topmost surfaces of the photo-receptive regions down into the substrate; and  
coupling metal fingers to the gridlines,  
wherein the substrate is 156 mm x 156 mm, the photo-receptive regions are doped using a system comprising a single-species delivery module, and a throughput of the system is at least 1,000 wafers per hour.